TECHNICAL UNIVERSITY OF LIBEREC

Faculty of Textile Engineering

Department of Textile Chemistry

DIPLOMA THESIS

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TECHNICAL UNIVERSITY OF LIBERC
Faculty of Textile Engineering
Department of Textile Chemistry

LASER LIGHT TREATMENT OF GLASS FIBRES

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Number of Pages	: 84
Number of Tables	: 14
Number of Figure	: 73
Number of References	: 25
Number of Appendices	: 11

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Acknowledgement

Ngibonga uMdali ngakho konke angenzele kona.

It's a pleasure to thank all the people who made this thesis assignment possible.

I would like to thank my dissertation counsellor Ing. Marie Štěpánková and my dissertation tutor doc. Ing. Jakub Wiener, Ph.D. for their guidance throughout my thesis. I would also like to thank every staff member that helped me at the Technical University of Liberec.

I would love to thank my mother (Mrs L.B. Goba) and father (Mr N.R. Goba) for everything they have done for me, and, of course, every family member (including relatives) and friends for all the support they have given me, it is sincerely appreciated.

And lastly I would also like to thank the KwaZulu-Natal Department of Economic Development for funding for my studies.

Ngiyabonga.

ABSTRACT

Glass fibres have many industrial applications such as filtration media and composite materials. Glass fibre applications are generally based on the type of glass fibre, constitutional composition, and the structural ordering of the glass fibres in the final structure, such as nonwoven glass fibre mats used as filtration media. Nonwoven glass fibre mats may be available in variable thickness dimensions. Glass fibre is a dielectric material and is therefore able to absorb energy from a carbon dioxide laser light beam. The carbon dioxide laser produces many watts in a single spatial mode that is then concentrated on a small area. The energy produced is in the thermal infrared region at approximately 10.6μm. When glass fibres absorb heat energy from the carbon dioxide laser beam they heat up, melt and then change definition, depending on the amount, rate and how the energy is applied. The main objective of this research was to determine the thermal effects caused by the laser light beam produced by the carbon dioxide laser on the glass fibre mat, and to determine incorporation of metal oxides during laser light beam treatment.

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INTRODUCTION

Glass is rated as one of the most important materials that may be used for a number of applications. Glass has a high transmission from the ultra-violet to the infra-red wavelength region. Glass has a very high chemical resistivity, excellent thermal and electrical properties (electrical insulation), but these properties vary according to the glass content, and this being the type of glass, and the way the glass was manufactured. These glass properties are and may therefore be controlled during the manufacturing process so to meet the desired specifications. [1] With the advancements of technology, namely the glass industry, the glass has become an important engineering material in architecture, automotive, medical, flat panel display and the electronics industry. The desired properties of the glass can only be achieved through accurate and precise processing techniques.[2]

Glass fibre is affected by many environmental factors during its use and further processing into the desired final product. The stability of the glass fibres is therefore not only based on how it was processed and its contents but also by the application it is used for.

Glass fibre has the ability to absorb laser light beam energy from the carbon dioxide laser beam, the glass fibre mat will therefore be treated with this laser light beam. The glass fibre heats up, melts and changes its definition accordingly to the amount of laser light beam energy applied. This heating and melting may further affect the structure of the glass the glass fibre mat. The glass fibres may shrink in length thus forming spherical endings and or they may melt and bind with neighbouring glass fibres. The formation of bonds with the neighbouring glass fibres may result in larger rigid solid structures which are greater in strength compared to original fibres. This heating, melting and bonding may affect the definition of the glass fibre mat, the glass fibre mat may lose its definition and the fibres may form over-bonded structures. Over-bonded and under-bonded glass fibre mats behave differently because of the bond spot such that it affects the fibres entering the bond spot.

Glass fibre occurs in different forms and the difference is mainly based on the chemical composition, this difference in its chemical constituent means different mechanical properties, chemical properties and thermal properties. The melting and cooling of glass fibre during the

absorption of energy in the form of heat should theoretically allow for the incorporation of metals in the form of metal oxide powders. Metal oxide incorporation will be done using the energy from the carbon dioxide laser beam. The treated glass fibre mat will then be analysed mechanically and via image analysis spectra after laser light beam treatment.

1.1 GLASS FIBRE

Textile glass fibres usually have a round cross-section with a maximum diameter of 18μm and the commonly used glass fibres have a diameter which is about 8μm to 12μm.[3] Glass fibre may be used for quite a number of applications, and these being;

1.1.1 Insulation

For glass fibre insulation, the thermal conductivity and sound transmission properties are the very important factors. The thermal performance of the glass fibre is directly related to its low thermal conductivity and density. When air is entrapped inside the glass fibre a very good thermal insulating material is formed, which has a thermal conductivity of about 0.5W/(m.K). The fibre diameter and configuration determines the efficiency of entrapped air, the fibre diameter and configuration are a fibre spinning technique.[4]

1.1.2 Filtration

Filtration is the separation of the dispersed phase from a continuous phase (carrier phase).[3]

The important factors for filtration are:

1.1.2.1 The surface area of the glass fibre

1.1.2.2 The size of spaces between the glass fibre

1.1.2.3 The diameter, the finer the diameter the greater the insulation and filtration effectiveness, such as the pore size of a glass fibre mat.[4]

The glass fibre non-woven structure allows for an increased filtration efficiency, the randomness of the structure give the particles a greater opportunity to strike and to adhere to the individual fibres. Quite a number of properties may be influenced by the method of production such as porosity which is the flow resistance related to flow volume (continuous phase) excluding dispersed phase. Other properties are stiffness, tear and bursting strength, thickness, etc. Properties determined by the filtration process are chemical stability, heat resistance, efficiency or mass penetration, resistance to bacteria, etc.[3]

1.1.3 Reinforcing fibres

Glass fibres may be used as a reinforcing agent in many polymers resulting in fibre-reinforced polymers which is the abbreviated to FRP, or glass-reinforced plastic, GRP. This glass reinforced plastic is also known as fiberglass. The reinforced polymer or plastic may then be known by its reinforcing fibre such as “carbon fibre” which may refer to the carbon fibre itself of the reinforced composite material.

The strength of a material is determined by the presence of flaws of critical dimension, and the greater the number of flaws the weaker is the fibre. Therefore for glass fibre, the number of flaws of critical dimension are reduced by increasing the surface to volume ratio which then leads to a glass fibre with greater or increased strength properties. The strength of the fibre is gauge dependent, and this means that when the fibres are bundled up, progressive failure is noted, the individual fibres have different strengths. This effect may be prevented via the formation of a composite material even though Youngs’ modulus of inorganic glass is approximately 20 times greater than that of the polymer resin that holds the glass fibres together as a composite material.[4]

1.1.4 Optical fibres

Optical glass fibres are made from polymeric, polymethyl methacrylate, and inorganic glasses. These glass optical fibres transmit digitalized data as electromagnetic waves. The clad optical fibres are able to transmit data for many kilometers without the need for signal boosting. Most optical fibres consist of a silica glass core-clad structure which is made as bulk preform and drawn into an optical fibre of diameter approximately 125μm. Germanium, phosphorus, boron are introduced as dopants to give the required refractive index profile, namely a core of approximately 8μm and refractive index enhancement of 0.001 to give a monomode fibre. Wide core multimode fibres have been developed where fibres of high numerical aperture are needed such as for medicine, image transmission.[4]

1.2. GLASS FIBRE CONTENT

Inorganic glasses are all based on silica which is an excellent glass former.

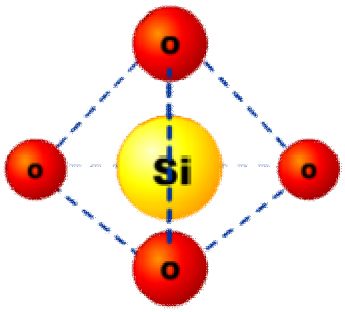

Figure 1 : SiO_4 tetrahedra.[20]

The polymerisation of the silica occurs via $[-SiO_{4/2}-]_n$ 3D networks. Glass has no sharp melting point and the glass structure starts to soften at approximately 1200^oC, even though it is soft it is not fluid enough for spinning until it reaches about 2000^oC. When the silica starts to crystallize, the networks made up of cyclic groups such as $[Si_6O_{18}]^{12-}$ containing 6 SiO_4 tetrahedra, sharing corners, and as embodied in crystalline forms of SiO_2 such as tridymite (high temperature polymer of quartz) and cristobalite (high temperature polymer of quartz) form. Crystal formation is disastrous for glass fibre manufacture because submicroscopic particles behave like strength-reducing flaws and cause problems in the fibre spinning process. Small rings occur in various silicate minerals and probably contribute to the disorder present in vitreous silica. Aluminum oxide (Al_2O_3) and boron oxide (B_2O_3) when present in significant concentrations and act as network formers of glass and are built into the network as tetrahedra, eg; albite mineral $NaAlSi_3O_8$. [10] B_2O_3 also reduces the liquidus temperature of a glass melt and the fibre forming temperature, while not affecting the mechanical properties of the fibre, addition of fluorine (CaF_2) also has a similar effect.[5][21]

The structural and internal order of the glass fibre determines the modulus or the stiffness of a fibre, and as the structural order increases so does the modulus increase. The internal structural uniformity and surface uniformity are a measure of the glass fibre strength. Generally alumina is a strong powerful modulus modifier because it increases the crystallisation potential of a given glass melt and therefore the internal order and the modulus of the resulting glass fibre. If the glass fibre has a very high moduli then it becomes a ceramic glass fibre.[5]

Some oxygen ions in the network have unsatisfied charges and their neutrality is brought about by incorporating network modifiers such as CaO, BaO, Na_2O and K_2O. These modifier ions are

located near unsatisfied oxygen ions in the interstices in the network. At high temperatures they start to break up the network and therefore results in the formation of non-bonding oxygens. Alkali bromosilicate glasses can form stable glasses that can be spun at high temperatures (form 1300^{o}C to 1600^{o}C) and have high chemical durability. Intermediate oxides such as Magnesium oxide (MgO) Titanium oxide (TiO_2) can also be found as network formers or modifiers. Sodium ions (Na^+) and potassium ions (K^+) are relatively mobile and so they contribute to the glasses electrical conductivity. At high temperatures the glass conductivity is significant, while at ambient conditions surface conductivity may occur. Volume resistivity of A-glass is 10^{10}ohm m and for E-glass 10^{15}ohm m.[4]

More than 99% continuous glass fibres are spun from an E-glass formulation [4]. The contents of the glass fibre play a very important role, the modifiers tend to increase the modulus or the stiffness of the glass fibre. Alumina and baria tend to increase the density of the glass fibre, while alumina and strontia tend to increase the refractive index, and zinc oxide and zirconia tend to increase the alkali resistance of the glass fibre.[5]

1.3. TYPES OF GLASS FIBRES

1.3.1 A-Glass fibre

A-Glass, also known as soda-lime, is an alkaline-lime glass which has little or no boron oxide, it was the first type of glass used for fibre but was not vey resistant to alkali. This glass has half the strength of E-glass fibre.[21]

1.3.2 AR-Glass

AR-glass is an alkali resistant glass which is used for cement reinforcements [1]. This glass fibre is highly sodium oxide (Na_2O) and Zirconium oxide (ZrO_2) modified. [5][21]

1.3.3 C-Glass

C-Glass is alkaline-lime glass which has a high boron oxide content. It may be used for staple glass fibres. C-Glass was developed to resist mainly acidic chemicals and is an E-glass alternative for bitumen reinforcement (roofing mats).[21]

1.3.4 D-Glass

D-Glass is a borosilicate glass with a high dielectric constant but has a lower dielectric constant when compared to E-glass fibre.[21]

1.3.5 E-Glass

E-glass is an alumino-borosilicate glass that has less than 1% by weight of alkali oxides (calculated as Na_2O), but its actual content varies. It is mainly used for reinforcing plastics. This was the first glass fibre formulation used for continuous filament formation. E-glass has excellent chemical durability, but its surface may be attacked and dissolved by chloride ions. It is not resistant to acid or alkali. Most E-glass contains a small quantity of fluoride to assist dissolution of raw materials and to lower the liquidus temperature (the liquidus temperature is the highest temperature at which a glass would develop crystals if held there for a long lime). Fluoride is one of the components in the glass composition that presents a pollution hazard since it volatilises as fluorosilicic acid, hydrofluoric acid and fluoroborates. Fluoride-free E-glass has been developed by optimising the MgO content at 1.8%, when the liquidus temperature is at a minimum of 1083°C and the fibre-forming temperature is lower than for traditional E-glass (1212°C). Fe_2O is an adventitious component that increases the rate of heat loss through infrared radiation when the molten glass leaves the bushing and can assist fibre forming, but the disadvantage is that Fe in the glass may be involved in acidic degradation reactions.[6][21]

1.3.6 E-CR-Glass

E-CR-glass is an alumino-lime silicate glass which has less than 1% by weight of alkali oxides. It has a high resistance to acids[21]

1.3.7 R-Glass

R-glass is an alumino-silicate glass that does not have MgO and CaO. It has high mechanical requirements.[21]

1.3.8 S-Glass

S-glass is an alumino-silicate glass without CaO but has a high content of MgO. It is used for high strength formulations and is used when tensile strength is the most important factor.[21]

1.4. NONWOVEN GLASS FIBRE MAT

1.4.1 Properties of Nonwoven Glass Fibre Mat

The properties of nonwoven fabrics depend mostly on the type of fibres used, the way the fibres are arranged or structured and the bonding mechanism in between the fibres. The bonding mechanism regardless of the process utilized, the fibres in the nonwoven structure are bonded by chemical, mechanical, or by thermal means. In most nonwovens structures, the majority of fibres are planar *x, y* stacks of fibres which have little or no orientation through the plane, *z* direction. The most important structural orientation is the *x* and *y* orientation because only a very small percentage of fibres are oriented in the *z* direction. *x, y and z* being the dimensions.[7]

When a simple deformation is applied to the glass fibre along a direction around which the initial orientation distribution is symmetric, it will remain symmetric through the deformation process, but if it is applied along a different direction, the symmetry could be lost with respect to the initial symmetry direction, but develop progressively with regard to the test direction.[7]

1.4.2. Failure Mechanisms in Nonwoven Glass Fibre Mats

The main source of failure in nonwoven glass fabrics are defects, these defects may be split into two categories, viz; 1) non-uniformities which originate mostly from the web formation 2) bonding properties such as over-bonding and under-bonding of the glass fibres. Once the failure has been initiated, its propagation is essentially ruled by the orientation distribution function (ODF).[7]

1.4.3. Basis Weight Uniformity of Nonwoven Glass Fibre Mat

Basis weight uniformity refers to the degree of mass variation in a nonwoven material which is measured over a certain scale. Local variations of nonwoven is the unattractive appearance and these lead to and may dictate failure point of glass fibre nonwoven fabrics. Tensile failure is initiated and propagated first in regions of low mass, index of uniformity for nonwovens, or barrier properties are lost because of the existence of low mass regions. The index of uniformity is the direct measurement of the coefficient of variation of the weight of numerous nonwoven glass fibre samples of a given size. There is a difficulty in determining the basis weight uniformity because it lies in the fact that the measurement is often size dependent.[7]

1.4.4. Underbonding

Under-bonding occurs when there are an insufficient number of chain ends in the molten state at the interface between the two crossing fibres or there is insufficient time for them to diffuse across the interface to entangle with the free ends of the chains in the fibre, or is when insufficient melting has occurred or too little time for diffusion was allowed prior to cooling. The fibres in the bond still maintain shape and structure because significant melting has not occurred. This therefore results in a few chains and the bonds can be easily pulled out or rapture under load. For bonds to occur, partial melting of the crystals should also occur so to permit chain relaxation and diffusion.[7]

1.4.5. Overbonding

Over-bonding is caused by too much melting of the glass-fibres, significant melting and shrinkage occurs and the fibres begin to or have lost their structural definition. Many chains diffuse across the interface, and a strong solid bond forms. The fibres within the bond spot lose their orientation and strength, but the bond spot itself represents a much more rigid and larger area compared to the fibres entering the bond spot. The glass fibres that are over bonded lose some of their molecular orientation and strength at the fibre bond interface. The bonding site edge becomes the stress concentration point where now weaker fibres enter. When the glass fibre is loaded, mechanical mismatch occurs and it results in premature failure of fibres at the bond periphery.[7]

1.5. SURFACE CHEMISTRY OF GLASS FIBRE

Glass fibres are widely used in the manufacture of structural composites. They exhibit useful bulk properties such as hardness, stability and resistance to chemical attack, as well as desirable fibre properties such as strength, flexibility and stiffness. E-glass, principally developed for its excellent electrical properties, has become the universal glass for fibre reinforcement because of its excellent chemical durability and relatively low cost.[8]

Borosilicate glass contains metal ions on the surface which may be removed by leaching, leaching also increases the silanol surface density.[16] Silicon, oxygen, calcium, aluminium, magnesium, sodium, and boron are the main elements in an unsized E-glass fibre surface.[8] The SiO_2 composition typical of E-glass fibre is 55%.[9] The glass fibre contains mostly silanol groups on its surface [10]. Glass fibre is made in the presence of water, therefore the silicone at the surface will have hydroxyl groups attached and this also means that hydrolysed silane will compete with silanols on glass surface through self-condensation. For strong active surface, such as silicate minerals, the triol will tend to be adsorbed, eg: γ-aminopropyltriethoxysilane (γ-APS)-internal H-bonding stabalises the adsorbate, forming a monolayer, but with glass surfaces, multilayers are deposited. Approximately more than 100 layers are deposited and approximately 90% are readily extracted with water at 50^{o}C. 3 to 6 layers may remain after rigorous hydrolytic extraction at 80 to 100C, therefore this leaves a highly hydrolytically resistant deposit, and these

layers are referred to; physisorbed layers, loosely chemisorbed layers and strongly chemisorbed layers.[4]

1.6. INCORPORATION OF METALS IN GLASS FIBRE

There also exist degradable glass fibres such as phosphate-based type of glass fibres, the rate of degradation can be linear with time and is influenced by the glass composition. The phosphate tetrahedra provide the basic building structure and therefore each phosphate tetrahedron can be attached to a maximum of three other phosphate tetrahedra as in phosphorus pentoxide. This will then allow metal oxides such as calcium oxide and sodium oxide to be added as network modifiers. The rate of degradation of these glass fibres may be controlled, such as increasing the calcium oxide content, the rate of degradation of the glass will decrease. This also allows the controlling of the glasses chemical durability by doping the phosphate-based glasses with various ions such as aluminium, iron and magnesium. The iron oxide (Fe2O3) increases the cross-link density which produces a more durable glass by significantly reducing the rate of degradation. The chemical durability of phosphate glasses also greatly improved by addition of zinc oxide because the zinc ion also acts as an ionic cross linker between different phosphate anions therefore inhibiting hydration reaction.[18] The metal oxides also aid in the increase in conductance with (increase in transition metal ion).[19]

1.7. CHEMICAL STABILITY OF UNCOATED GLASS FIBRES

The chemical stability of glass fibres, fibres which have either acid or base finish resistance depends on the interaction between the chemical agents to which the glass fibre is exposed, the pH of the glass composition on the fibre surface and also the internal microstructure of the fibre. For an alkali-free or a nearly alkali free glass fibre, water gets adsorbed and causes hydrolysis of the siloxane bond by protogation of the oxygen atom, this hydrolysis therefore leads to a highly hydroxylated fibre surface, SiOH.[17]

For glass fibres which contain high amount of alkali, the reaction of water with the glass surface represents an electrophilic attack by the addition of a proton, H^+, to the negatively charged

oxygen atom of the Silicon-Oxygen-Metal bond. The reaction is an ion exchange between the proton and either alkali ions and/or network modifying alkali earth ions, this also results in an SiOH surface. When the H^+ are exhausted, this corrosive attack turns into a nucleophilic attack by the alkali ions on the glass fibre surface, i.e.; the glass fibre reacts with the alkali and it results in the breakdown of siloxane bonds and formation of SiO-Na bonds, the glass fibre therefore completely dissolves in the alkali medium that initially only consisted of water molecules.[17]

In an alkali media the hydroxyl ions nucleophilically attack the silicon atoms in the bare surface of a glass fibre resulting in SiOH or SiO-M. The monovalent cations such as sodium are removed from the glass fibre surface thus leaving behind a hydroxylated surface, while the bivalent cations remain attached to the glass fibre and form a crystalline sheath that grows in thickness. The sheath develops when the SiO_2 or Al_2O_3 is greater than 50%, in bare silicate fibres, is exposed to an alkaline medium. The crystalline sheath consists mainly of $Ca(OH)_2$ and it increases the alkali resistance but reduces the fibre strength.[17]

Mineral acids selectively dissolve specific components of the glass fibre, initially the ions of network modifiers. As a rule, the Silanol bonds are not broken and the SiO_2 is not dissolved. The cations can selectively dissolve in acid media if the amount of SiO_2 is not sufficient to create a continuous network structure. Addition of oxides such as Zr (ZrO_2 increases both acid and base resistance), Ti and Fe even to high alkali oxide glasses may substantially increase the acid resistance of the glass fibre, but in the end the entire fibre is converted into a porous high silica fibre. All fibres excluding the experimental single fibres, have a primary finish and some may have an additional secondary finish.[5]

1.8. ALKALI AND ACID RESISTANCE OF GLASS FIBRE

1.8.1. Alkali Resistance

The application of an alkali resistance finish or a secondary coating renders glass fibre suitable for continued use as a durable reinforcement of cement structures, such as alkali resistant glass

fibre (AR-Glass fibre), whether they are composite wraps for bridge columns, net-like structures specifically aimed at roadbed construction.[5]

1.8.2. Acid Resistance

The high acid resistance of glass fibres is similar to the behaviour of glass fibres that contain large amounts of silica such as pure silica fibres, or contain high amounts of alkali. Four groups of glass have higher acid resistance than E-Glass fibre, and these are:

1.9.2.1 Generic boron free E-glass

1.9.2.2 High strength (HS) glass fibre, high modulus (HM) glass fibre and pure silica quartz fibres

1.9.2.3 High silica fibres obtained from E-glass by leaching mineral acids

1.9.2.4 High alkali silicate fibres. These glass fibres include C-glass, which has a more desirable forming temperature than A-glass. The forming temperature of A-glass and C-glass is more desirable (is lower) than that of E-glass

A high amount of alkali content means the glass is more resistance to acids when compared to E-glass.

1.9. GLASS FIBRE MANUFACTURE

1.9.1. Manufacture Process

Glasses are most frequently produced by a melt cooling below its glass transition temperature sufficiently fast to avoid formation of crystalline phases.[6] Glass fibre is formed when thin strands of silica-based, SiO_2, which exists as a polymer in its pure form or other formulation glass is extruded into many glass fibres with suitable diameters for textile processing. Pure silica is a viable glass and glass fibre that is worked with at high temperatures. This working

temperature may be reduced by adding impurities into the glass fibre, which may lead to beneficial application properties. Glass fibre is manufactured as staple and as continuous filament glass fibre. The manufacture involves the preparation of marbles, which are melted in the fibresation stage.[4]

A furnace is continuously charged with raw materials which are melted and refined as the glass reaches the foreheath above the set of Platinum-Rhodium bushings from which the fibres are drawn. During drawing the glass must have a low and narrow viscosity (between 600 and 1000 P) so to prevent breaking. The viscosity must not be too low since this may lead to the formation of bubbles. Glass fibres are produced by rapid attenuation of molten glass exuding through nozzles under gravity. The production rate at the nozzle is a function of flow rate of glass and not attenuation rate, the attenuation rate only determines the final diameter. The Poiseuille's equation- describes the flow of molten at the nozzle

$$\mathbf{F= (r^4h)/(\mathit{l}\eta)};\ldots\ldots\ldots

surface increase in the process from melt into fibres. The high cooling rates of glass fibres causes freezing-in of the liquid structure of the melt at a temperature that might be considerable higher than the glass transition temperature. This temperature is called the fictive temperature, T_f, and it depends on the cooling rate. Differences in both compositional and structure related properties are observed in glass fibres. The low density of glass fibre reflects a more open network structure in glasses including high fictive temperatures. Less heterogeneity in the glass structure of high T_f glass due to the fast cooling of more isotropic melt is argued to introduce higher strength of high T_f glasses. It was argued that the high cooling rates of fibres would produce internal stresses that would contribute positively to the high strength of glass fibres. However, no internal stresses exist in fibres of approximately 10μm in diameter due to a different cooling rate at the skin and interior of the glass fibres. High T_f exhibits easier flow and densification, which result in easier deformation and faster stress relaxation. Subcritical crack growth rates in soda-lime-silicate glass shows slower crack growth rate in glasses of higher T_f. According to slower subcritical crack growth, the higher cooling rates (higher T_f) are expected to result in higher mechanical strength when tested in ambient air. The fictive temperature of the glasses can be determined from differential scanning calorimetry.[11]

1.9.3. Fibre Finish

After cooling the fibres are coated with an aqueous size (usually an emulsion) which is in contact with a rubber roller. The finish is also applied so to maximize the protection of the fibres for further processing or manipulation. The finish may consist of the following:

1.9.3.1. An adhesion promoter or coupling agent. The solid content of the solid binder will be approximately 10% of which 0.3 to 0.6% will be the coupling agent.[4]

1.9.3.2. Protective polymeric size or film former. The film former is a polymer (may contain a plasticizer) at high boiling point, eg; dibutyl phthalate. The film former also influences the nature of deposits on the glass surface. The film former is chosen for one or more of the following reasons; Compatibility with coupling agents, stability of the emulsion during application,

handling characteristics after drying, unwind potential for unpacking, wet-out rate in the resin and dry and wet properties of the composites.[4]

1.9.3.3. Lubricants. Lubricant 0% to 0.35%, surfactant (0% to 0.5%), assistant (0% to 0.35%) usually present in the emulsion. Lubricants and anti-static agents are mostly based on fatty acid amides and in the presence of acetic acid (adjust pH of sizing emulsion to approximately 4) it gets protonated, therefore quarternary ammonium sites are positively charged. Polyalkylene glycols are also used.[9]

1.9.3.4. Surfactants

1.9.3.5. Antistatic agents. Since glass is a non conductor of electricity, static electricity builds up during the use of rovings at high speeds. Therefore to impart surface conductivity, antisatatic agents are used such as alkyl trimethyl ammonium (Arquad S50) and quaternary ammounium sulphate (Neoxil AO 5620).[4]

1.9.3.6. An optical polymeric binder (emulsion or powder) used for fibre mats.

** *(1.9.3.2 to 1.9.3.6- impart good hand ability).*[4]

1.9.3.7 Silane (SiH_4) and other coupling agents

These are adhesion promoters added to sizing emulsion so to provide glass with compatibility and potential coupling of glass surface to the matrix resin. This is done so to:

1. Displace desorbed water on glass surface

2. Create a hydrophobic surface of the correct thermodynamic characteristics for complete wetting by the matrix resin

3. Develop strong interfacial bonds between fibre and resin. eg; in the case of thermoplastics, long molecular chains that are into the polymer in analogy to graft.[4]

1.10. STRENGTH AND STIFFNESS PROPERTIES

The strength of glass fibre is tested for virgin or pristine glass fibres, the freshest and thinnest glass fibres are the most strongest and most ductile. Glass fibre has an amorphous structure and therefore the properties are similar along and across the glass fibre.

The modulus, 70GPa to 80Gpa, is very much dominated by the chemical forces that operate within the amorphous inorganic glass fibre. High modulus of glass fibre is achieved only with crystallisation into a glass-ceramic or ceramic. At a critical size given by the Griffith equation, rapid fracture occurs. The population of flaws and their size of the flaws determine the material failure, therefore a fine filament with lower density of critical flaws will be stronger than the bulk solid.[4] Directionality or spin orientation tends to increase the strength of individual fibres. A uniform network structure translates into high tensile strength and a highly non-directional arrangement (random) of calcium oxide and aluminum oxide in a rapidly solidified binary calcium aluminate fibre translates into very low tensile strength. Amorphous glass, nanocrystalline glass ceramic and polycrystalline ceramic fibres have different strengths due to the differences in the internal order of the fibre structure.[5] As a rule of thumb the theoretical strength is E/10, which for glass fibre is approximately 7Gpa, but the practical strength would be significantly less at approximately 0.07GPa. A typical E-glass fibre can have a 3Gpa strength.

Glass fibres exhibit three populations of flaws;

1.10.1 The average strength of 3Gpa could be attributed to severe surface flaws of 20mm spacing.

1.10.2 The average strength of 3 to 5 GPa could be attributed to mild surface flaws of 0.1mm spacing associated with a tempered layer 10nm thick which is fractured to expose the inner core whose length is determinant.

1.10.3 The average strength of 5GPa may be attributed to internal defects of 10^{-4} spacing, characteristic of defect free filaments with an untempered surface layer.[4]

1.11. LASER

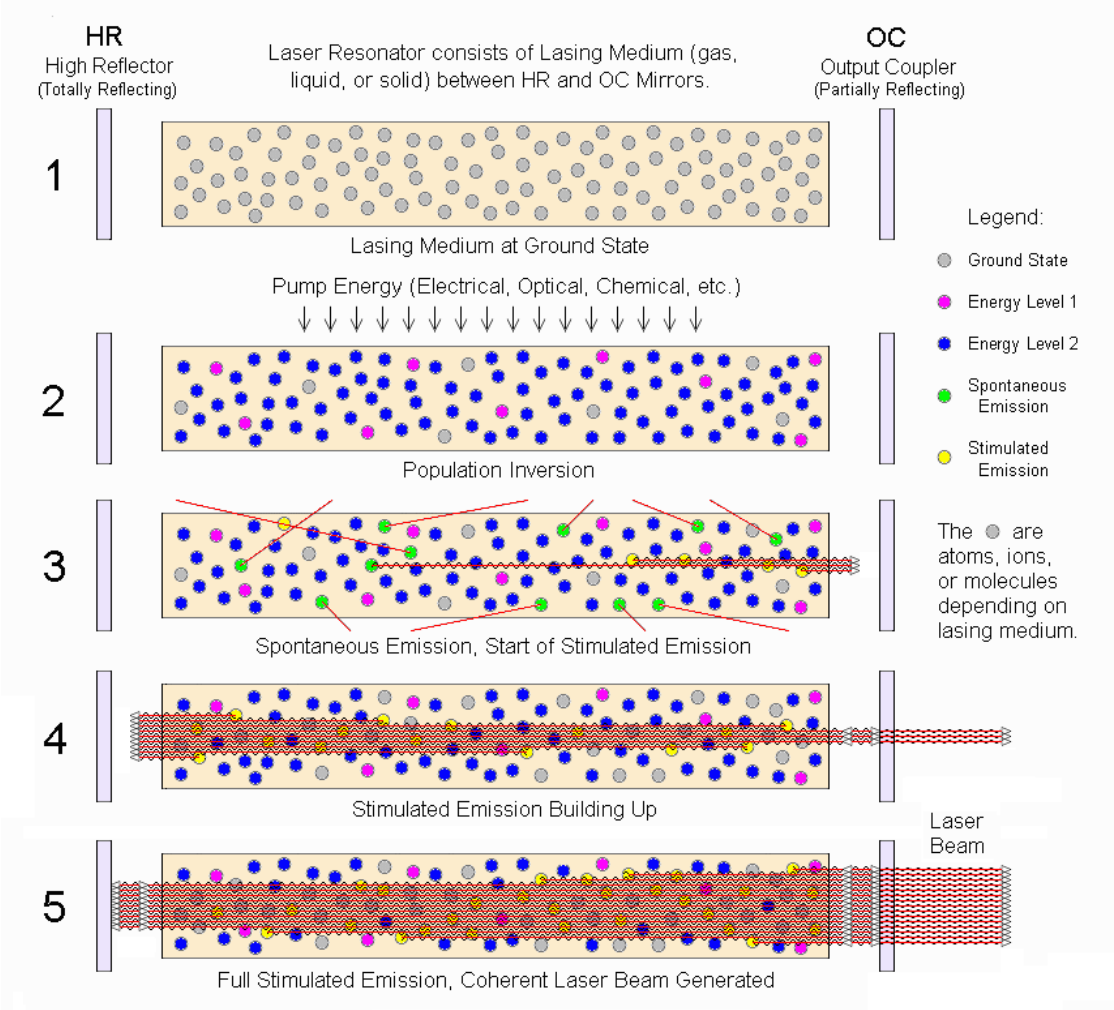

Figure 2 : A schematic overview of the functioning of a laser, laser beam generation.[25] The HR and OC in the figure are reflecting mirrors that bounce the light back and forth inside the optical cavity. This allows the light to be amplified in the gain medium

1.11.1. Carbon Dioxide (CO_2) Laser

The carbon dioxide laser is one of the most powerful and efficient lasers. It is a four level molecular laser and operates on a set of vibrational-rotational transitions. The laser output is in the middle infrared at 10.6 μm and 9.4μm wavelength region. Both continuous wave (cw) and pulsed output occurs. The laser produces cw powers greater than 100kW and pulsed energies of as much as 10kJ (0.167kW).[22][24]

1.11.2. Energy Levels of CO_2 molecule

In case of isolated atoms, the electron energy levels are discrete and narrow. On the other hand, the energy spectrum of molecules is complex and includes many additional features. Each electron level is associated with a number of vibrational levels and each vibrational level in turn has a number of rotational levels. The CO_2 molecule is a linear molecule consisting of a central carbon atom with two oxygen atoms linked on either side of the carbon atom. The CO_2 molecule may undergo three independent vibrational oscillations which are termed vibrational modes, viz; stretching mode, bending mode and the asymmetric mode. Each mode is quantized, so the molecule can have 0, 1, 2 or more units of vibrational energy in each mode. At any one time, a CO_2 molecule can vibrate in any linear combination of these three fundamental modes. The energy state of the molecule is then represented by three quantum numbers (m, n, q). These numbers represent the amount of energy associated with each mode, eg; (020) indicates that the molecule in this energy state is in the pure bending mode and has two units of energy. Each vibrational state is associated with rotational states corresponding to the rotation of the molecule about its centre of mass. The separation between vibrational-rotational states are much smaller on the energy scale compared to the separations between electron energy levels. The CO_2 laser is a discharge tube having a bore of cross section of about $1.5cm^2$ and a length of about 26cm. The discharge tube is filled with a mixture of carbon dioxide, nitrogen and helium gases in 1:4:5 proportions respectively. Generally, a high dc voltage causes an electric discharge to pass through the tube. The discharge breaks down the CO_2 molecules to form oxygen and carbon monoxide. Therefore a small amount of water vapour is added to the gaseous mixture which regenerates CO_2.[12][22]

1.11.3. Easy Laser Marcatex Flexi CO_2 laser

The wavelength ejected beam of a carbon dioxide laser may be in the range of 9.3μm to 11.5μm. This range of wavelength is invisible to the human eye. This laser emits high power infra-red radiation beam which is invisible to the human eye, even though in most cases it behaves like a visible light. When the beam is focused it may be sufficiently powerful to cut through materials. This laser beam may be absorbed by most dielectric materials such as water, biological fabrics, plastics and it is instantaneously absorbed by the first absorbent material it finds in its path. This laser beam may be reflected by smooth metallic surfaces even when the surfaces are darkened.

The carbon dioxide radiation may be may be concentrated with lenses to apply it to tasks such as cutting or engraving. The laser beam may quickly disperse beneath the focus point thus causing dissipation of the energy density or the beam density. The laser beam provides a hot beam which may be applied as a controlled method of heating or burning the surface of certain materials, eg; very fine flame torch.[13]

1.11.4. Basic Laser Operation

Lasers are monochromatic, this means that the laser is a very orderly form of light, unlike the incandescent light bulb which emits light of a variety of wavelengths and in all directions, light from a laser has only one wavelength and moves in only one direction. There are three energy levels within an atom that the electrons can be in. The electron can choose t be in whichever energy level, depending on the amount of energy it has. The most stable system is one with the lowest energy and electrons in any material are all in their lowest energy levels. Sometimes an electron might get excited to reach a higher energy state, but electron does not stay in that excited state for a long time. The electron will readily release energy to return back to its stable, low energy state or ground state. The electrons release the energy in any random direction and at any time after it has been excited. At any particular time, some electrons get excited, while others lose energy, so the system on average, remains in the lowest energy stable state. What's interesting is when most electrons are already mainly in the excited state. By pumping energy into the system, population inversion is achieved where there are more excited electrons than those in the lowest energy state. When the electrons start releasing energy it seemingly communicates with other excited electrons to release energy too and this phenomenon is known as stimulated emission. Therefore when there is population inversion, there is a chain reaction that takes place. When one electron returns back to its lowest energy state and releases its energy, it incites other electrons to do the same. Then plenty of energy is released at the same time. The only problem one is that the energies are released in random directions and this is overcome by strategically placing mirrors within a laser, this then makes sure that the energies emitted are all in the same direction. The energy packets are known as photons. As they bounce back and forth between the mirrors, they seem to be communicating with the excited atoms within the material, causing more stimulated emission. Even more energy is released as photons. The photons correspond to light of a particular wavelength. Therefore by achieving population

inversion, stimulated emission and strategic placing of mirrors, monochromatic, directional and coherent form of light is obtained, therefore a laser is produced.[22][23][24]

1.12. HEAT TREATMENT OF GLASS FIBRES

Glass fibres such as stone wool fibre (SWF), iron-bearing aluminosilicate glass system, have excellent high temperature stability (HTS). A good HTS implies that the fibres are able to retain their original geometric shape at high temperatures [2]. HTS of the fibres strongly depends on the atmosphere in which they are heated. When the fibres are heated in an oxidizing atmosphere at temperatures around 1000^{o}C, their shape and flexibility remain almost unchanged, but when the fibres are heated at the same temperature in an inert or reducing atmosphere, they shrink and sinter, and hence, lose their shape and become hard and brittle. In iron-bearing aluminosilicate glass fibres the ferrous ions are oxidised to ferric (Fe^{3+}) ions when SWFs are heated in atmospheric air at temperatures approximately above $0.8T_g$ (in K). The oxidation occurs by a diffusion process of divalent network-modifying cations towards the surface, and not a diffusion process of oxygen from the surface into the bulk of the glass. This so-called outward diffusion of divalent cations takes place to charge balance an inward flux of electron holes that move via the oxidation process of Fe^{2+} to Fe^{3+}. At the surface, the divalent cations react with the oxygen in the air, creating a nano-crystalline surface layer consisting primarily of MgO. The formation of the nano-crystalline surface layer has been found to be the predominant origin of the good HTS of SWFs in oxidising atmospheres. Therefore, it is possible to enhance the HTS by preoxidising (i.e., heat-treatment in air at temperatures around T_g) SWFs in atmospheric air. HTS of SWFs can be improved by increasing the MgO content. Mg^{2+} has relatively high field strength due to its small size and it therefore strongly attracts the nearby oxygen anions. This means that Mg^{2+} ions are capable of preventing the gradual deformation with increasing temperature to a larger extent than, e.g., Ca^{2+} and Na^{+} ions as they have lower field strength. Glass fibres heated in argon or air have the lowest value of T_g due to the relatively high content of alkali oxides (Na_2O and K_2O) in the fibres. Addition of alkali oxides to silica glass is well known to cause a decrease of T_g.[14]

1.13. LASER LIGHT TREATMENT OF GLASS FIBRE

Glass articles can be efficiently treated if one uses a carbon dioxide laser emitting at a wavelength of 10.6μm. The reason for this choice is that glass articles can conveniently be processed because they readily absorb the laser radiation at this wavelength. When a glass surface is treated by a laser beam, the material can be sublimated, evaporated, or fused, depending on the power density produced by the beam. Evaporation (106 - 107W/cm^2) reduces machining-tool marks and surface roughness. Laser polishing is reported to reduce surface roughness, to heal up surface cracks, to remove machining-tool marks, and to enhance the radiation-damage resistance of the material.[15]

Laser light treatment of glass can lead to glass cracks, these cracks may be prevented by doping the glass substrate with less than 10% Ag ions (Nippon Sheet Glass) which has a thickness of about 100μm. The silver ions may be used during laser machining of glass since they effectively minimise cracking and chipping. The above was investigated in order to obtain high quality laser micro-fabricated features on glass materials and was based on machining technologies based on nanosecond, fentomsecond and laser induced plasma processing.[1]

1.14. STRESS FIELDS DURING DIODE LASER CUTTING OF SODA-LIME GLASS SHEETS

Laser treatment may be used for a number of applications, for instance, the soda lime glass may be cut using laser light, a controlled fracture technique that has great potential in laser cutting which utilises less laser power and enables high cutting speeds compared to other laser cutting methods. This technique requires the soda lime glass to be cut below its glass transition temperature so it may result in smooth edges that require no further cleaning or grinding. The propagation of cracks in glass occurs if stresses in the soda lime glass exceed the failure stress which is given by the critical energy release rate, G_c.

$$G_c = (\sigma_f^2 \pi c)/E \quad \text{.....(2)}$$

In the controlled fracture technique cracks are initiated due to absorbed photons, heating up of the material occurs. These stresses near the laser spot are compressive due to the high temperature of the laser beam, but these compressive stresses relax and induce local residual tensile stresses, after the passage of the laser beam. The interaction of the CO_2 laser with glass results in surface absorption while the diode laser due to its low absorption coefficient produces volumetric absorption, thereby resulting in different thermal and stress fields in the glass. A volumetric heat source is when the optical penetration depth (absorption length) is greater than the thermal penetration depth (diffusion length). The depth of the heat affected zone depends on the absorption length as well as on the diffusion length. When the diffusion length is less than the absorption length, the depth of the heat affected zone is governed by optical penetration, A_d, and vice versa.[2] The thermal diffusion length, D_d, is given by the following equation;

β is the thermal diffusivity and t is the interaction time;

$$D_d = 2(\beta t)^{1/2} \quad \text{.....(3)}$$

2.1. EXPERIMENTAL

Glass fibre mat which is a nonwoven structured material was treated with a carbon dioxide laser beam using the Easy Laser Marcatex Flexi CO_2 laser (Marcatex 150/250 flexi). The glass fibre mat used in this treatment was an E-glass formulation. Two types, based on thickness, of glass fibre mats were used, viz a thick glass fibre mat which was 1.6mm thick and a small glass fibre mat which was 0.3mm thick. The table below shows the parameters of the glass fibre mats used, these being the non-treated glass fibre mat.

Table 1 : 0.3mm thick untreated glass fibre mat parameters

Properties	**Unit**	**Typical values**	**Standard**
Surface weight	*g/m^2*	75	ISO 536
Thickness at 50kPa	*mm*	0.3	ISO 534
Efficiency	*%*	99.9	ASTM D2986
Permeability at 200 Pa	*$l/m^2/s$*	40	ASTM D2986
Pressure Drop at 5.33cm/s	*Pa*	200	ASTM D2986
Breaking length	*m*	200	ISO 1924 – 2
Stretching along %	*%*	1.5	ISO 1924 – 2
Breaking Length across	*m*	150	ISO 1924 – 2
Stretching across	*%*	2.5	ISO 1924 – 2
Ash	*%*	99.5	ISO 2144

Table 2 : 1.6mm thick untreated glass fibre mat parameters

Properties	**Unit**	**Typical values**	**Standard**
Surface weight	g/m^2	270	ISO 536
Thickness at 50kPa	*mm*	1.6	ISO 534
Efficiency	*%*	99.99	ASTM D2986
Permeability at 200 Pa	$l/m^2/s$	10	ASTM D2986
Pressure Drop at 5.33cm/s	*Pa*	750	ASTM D2986
Breaking length	*m*	260	ISO 1924 – 2
Stretching along %	*%*	1.5	ISO 1924 – 2
Breaking Length across	*m*	200	ISO 1924 – 2
Stretching across	*%*	2.5	ISO 1924 – 2
Ash	*%*	99.5	ISO 2144

The Easy Laser Marcatex Flexi CO_2 laser (Marcatex 150/250 flexi) parameters are shown below:

Technical Characteristics

Model : Marcatex 150/250 flexi

Average Power : 150/250 Watts

Peak power : 230/ 400 Watts

Power supply : 220 ca -/+ 10% monophasic

Input voltage : 200 – 240V ca +/- 10% monophasic

Working frequency : 50/60 Hz +/- 1%

Consumption : Laser ON: 2.3KW, 8.7A con

Laser beam characteristics

M^2 (K) : <1.2 (>0.8)

Beam divergence : <2.5 mrad (complete angle)

Beam ellipticity : <1.2:1

Stability of beam direction : <200 mrad (half angle

Beam diameter ($1/e^2$) : 7.5 +/- 0.5mm. (for normal beam correction)

Wavelength : 10.6μm

Polarization : Linear (perpendicular to laser head base)

Cooling System

Type : external water cooling system

Power supply : 230V ca +/- 10%, 50/60 Hz

Consumption : 3.3KW, 14.6 A

Heat load : 2000 Watts max

Flow of cooling fluid : 4*l*/min. (minimum)

Cooling fluid temperature : 19- 25^{o}C (+/- 1^{o}C of adjustment)

Cooling fluid pressure : >2.2 bar (32 psi) > 6.0 bar (88psi)

Connections : 8mm diameter hose or feather joint for 3/8'' diameter hose

In-line filter : 100μm

Environmental Specifications

Temperature environment : +5 to 40^{o}C

Storage temperature : +10 to 70^{o}C

Humidity : 10 to 85% relative humidity (without condensation)

Altitude : < 3000m

The glass fibre mats were treated with varying laser beam intensities and also at single beam intensity at varying cycle times, all experiments were performed using a duty cycle of 50%. The thicker (1.6mm) glass fibre mat was exposed to greater laser beam intensities, while the thinner (0.3mm) glass fibre was treated at lower beam intensities. The glass fibre mats were placed on a flat surface below the laser beam head during treatment, so that as the beam irradiated the samples the laser beam was perpendicular to the treated samples.

2.1.1. Treatment of 1.6mm glass fibre mat

This glass fibre mat was treated with laser beam intensities of 100μs pixel time, up to 800μs pixel time at 100μs increments.

The glass fibre mat was also treated with increasing number of laser beam intensities, meaning that a single amount of laser beam energy was used to irradiate the glass fibre mat sample. The used intensity was 100μs pixel time, this intensity was used to treat the glass fibre mat up to 7 number of cycles.

2.1.2. Treatment of 0.3mm glass fibre mat

This glass fibre mat was treated with laser beam intensities of 10μs pixel time up to 240μs pixel time in increments of 10μs pixel time.

The glass fibre mat was also treated with increasing number of laser beam intensities, meaning that a single amount of laser beam energy was used to irradiate the glass fibre mat sample. The used intensity was 40μs pixel time, this intensity was used to treat the glass fibre mat up to 7 number of cycles.

2.2. TESTED PARAMETERS

2.2.1. Mechanical Properties

The glass fibre mat that was treated with a laser beam was then tested for mechanical parameters using the mechanical testing machine, Tira Test 2300. These mechanical properties were strength, modulus and elongation.

The samples were cut into dimensions of 30cm x 6cm samples. The 1.6mm thick samples was tested at a rate of 50mm/min and the 0.3mm samples were tested at a rate of 25mm/min. The samples were stretched until they exceeded their breaking length and the results were recorded. Untreated control samples were also tested for mechanical parameters.

Figure 3 : Tira Test 2300. Was used to test the mechanical parameters of the treated and non-treated glass fibre mat.

2.2.2. Infrared Thermometer Heat Determination of Laser Treated Glass Fibre Mat

An infrared thermometer was used to determine the amount of heat experienced by the glass fibre mat during laser beam irradiation. This procedure was only done for laser treatment cycles. During laser treatment of the glass fibre the infrared thermometer was pointed on the samples and as the laser beam passed over the sample, the amount of heat in degrees Celsius was recorded.

2.2.3. Permeability

The laser light treated samples were tested for air permeability using the Air Permeability Tester, FX 3300 LABOTESTER III.

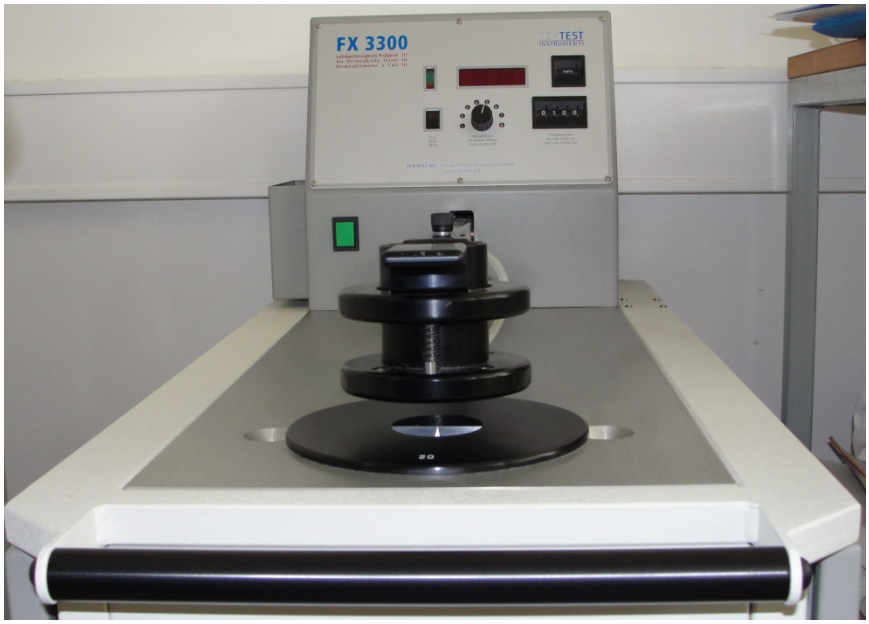

Figure 4 : Air Permeability Tester, FX 3300 LABOTESTER III. Was used to test the permeability of laser beam treated and non-treated glass fibre mat.

The treated samples were tested by passing air through them using the air permeability tester, a pressure of 200Pa was used to determine how much air was able to pass through the laser beam treated and non-treated glass fibre mat samples.

2.2.4. Thickness

Figure 5 : Uni-Thickness-Meter. Was used to test the thickness of the laser beam treated and non-treated glass fibre mat.

The laser light treated samples were tested for thickness parameters using the Uni-Thickness-Meter. The samples were placed on the measuring area which is 1000mm^2 and a pressure of 0.1kPa, 1kPa and 50kPa was used to determine the thickness of the glass fibre mats, for both treated and untreated samples.

2.2.5. Scanning Electron Microscope

The glass fibre mat samples, laser beam treated and non-treated samples were viewed using the Scanning Electron Microscope, SEM. The samples were cut into small sizes and were mounted rigidly on a specimen holder. When the samples were placed on the specimen holder, they were then coated with ultrathin coating of electrically conducting gold since the samples were non-conductive, this was done so to prevent them from charging when they were scanned by the electron beam. This coating prevented the accumulation of static electric charge on the glass fibre mat samples during electron irradiation.

2.2.6. Laser light Beam Incorporation of Metals into Glass Fibre Mat

Metal oxides were applied on the glass fibre mat by laser beam treatment. A small quantity (about 1mm thick) of the metal oxides in powder form was applied on the glass fibre mat. The glass fibre mat containing the metals was then irradiated with the laser light beam (100μs pixel time). After the laser light beam treatment, the samples were washed in running water and dried in a heated oven. The results of this treatment were then analysed using the Scanning Electron Microscope images and X-ray fluorescence spectra. The applied metal oxides were: Titanium, Zinc, Silver, Copper, and Iron.

3. RESULTS AND DISCUSSION

Glass fibre which is a dielectric material absorbed the carbon dioxide laser light beam that was produced by the carbon dioxide laser during treatment. The beam was in the wavelength range of 10.6μm. When the glass fibre mat absorbed such energies it heated up and when a lot of energy had been absorbed by the material it started to melt.

3.1. Mechanical Properties

The glass fibre mats that were treated with the carbon dioxide laser were tested for mechanical properties using the mechanical testing machine, Tira Test 2300.

3.1.1. Laser light beam intensity treatment

Table 3 : Tira Test 2300, mechanical parameters of the 1.6mm thick nonwoven glass fibre structure which was irradiated with a carbon dioxide laser beam with varying laser intensities and stretched at a rate of 50mm/min

Pixel time [μs]	F [N]	E [MPa]	ε [mm]	ε [%]
0	27.66	67.06	3.62	1.81
100	26.84	41.73	3.98	1.99
200	26.12	48.65	3.12	1.56
300	25.79	62.37	3.57	1.78
400	24.99	52.39	3.44	1.72
500	20.70	44.94	2.61	1.31
600	24.76	52.09	3.04	1.52
700	16.87	58.81	1.90	0.95
800	14.27	49.39	1.20	0.60

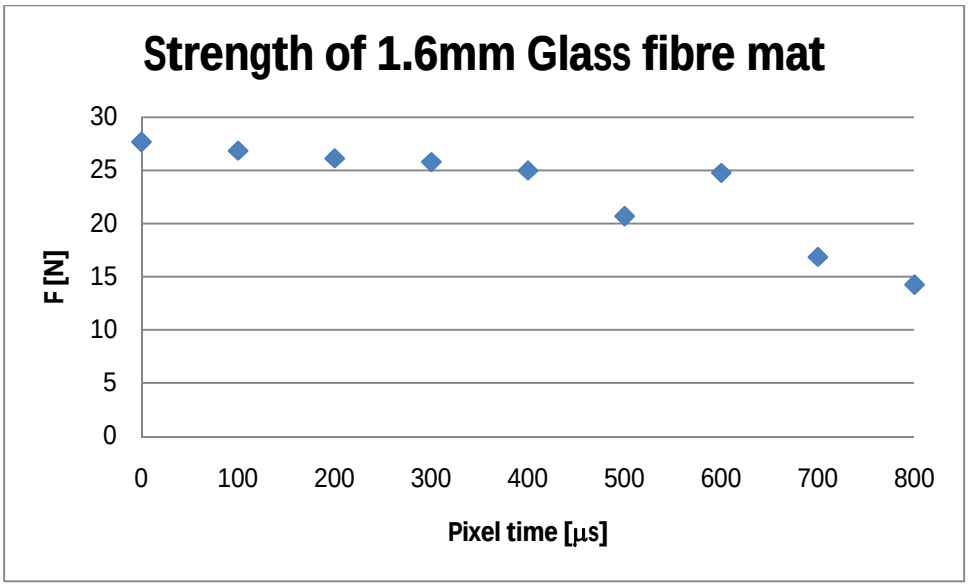

Figure 6 : the strength of the 1.6mm glass fibre mat samples treated with a carbon dioxide laser beam has strength values that decrease slightly as the intensity of the laser beam increases.

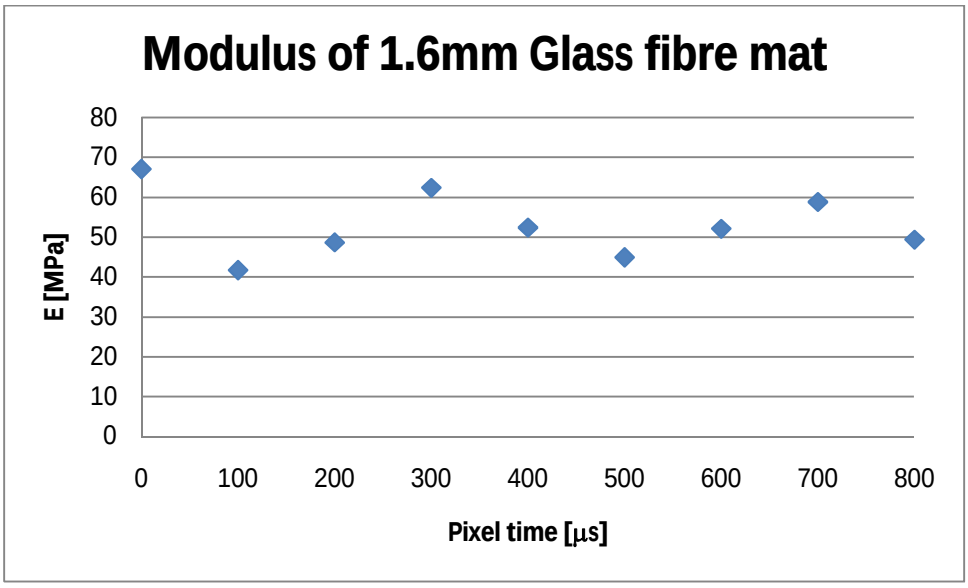

Figure 7 : the modulus of the 1.6mm thick glass fibre mat treated by a carbon dioxide laser beam at varying intensities is more or less constant, but less than the modulus of the untreated sample.

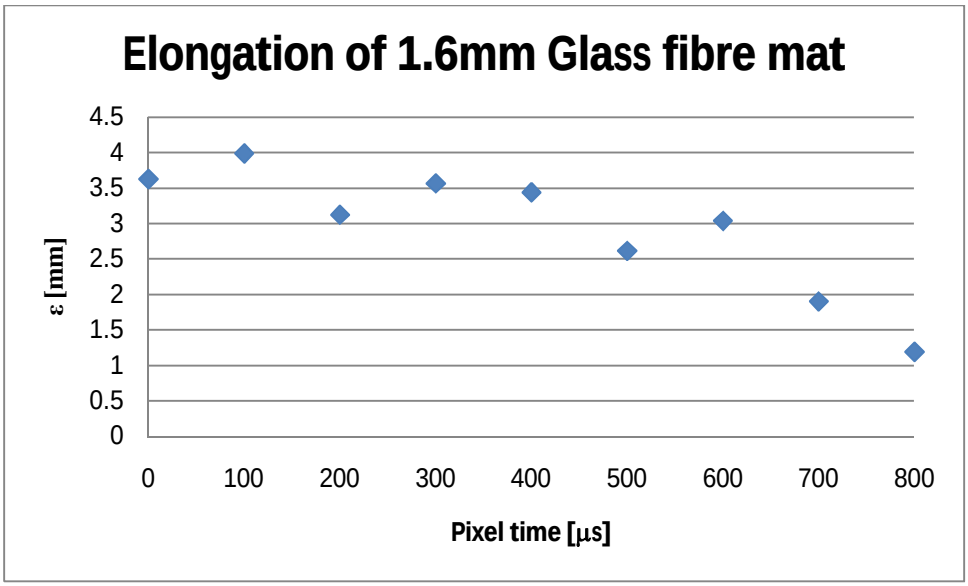

Figure 8 : the laser treated glass fibre mat (1.6mm thick) samples have elongation values that decrease as the laser intensity of the laser beam increases.

The 1.6mm thick glass fibre mat that was treated with the carbon dioxide laser beam at increasing laser beam intensity was tested for mechanical properties as shown in the above results. The tested parameters were strength F[N], modulus E[MPa] and elongation ε[mm]. As the laser beam intensity increased the mechanical properties of the glass fibre mat decreased. As shown in the above graphs the results in the graphs slope in the negative direction. The least negative slope of the graph was the modulus of the glass fibre mat, this was the result that showed a slight decrease when compared to the strength and elongation properties. Therefore using too much energy to treat the 1.6mm glass fibre mat leads to bad results since the glass fibre mat loses its mechanical properties.

Table 4 : Tira Test 2300, mechanical parameters of the 0.3mm thick glass fibre mat structure that was irradiated with a carbon dioxide laser beam with varying laser intensities and was stretched at a rate of 25mm/min

Sample	Pixel time [µs]	F [N]	E [Mpa]	ε [mm]
1	0	3.21	108.43	0.61
2	40	7.71	158.07	0.79
3	50	7.69	125.45	0.91
4	60	7.61	137.57	1.20
5	70	7.46	118.84	1.24
6	80	7.07	118.94	1.41
7	90	6.58	118.09	1.16
8	100	6.42	146.62	0.94
9	110	6.09	152.03	1.03
10	120	5.27	124.62	0.74
11	130	4.70	138.36	0.58
12	140	4.58	170.83	0.55
13	150	2.91	113.77	0.66
14	160	1.67	115.12	0.20
15	170	1.08	101.82	0.20

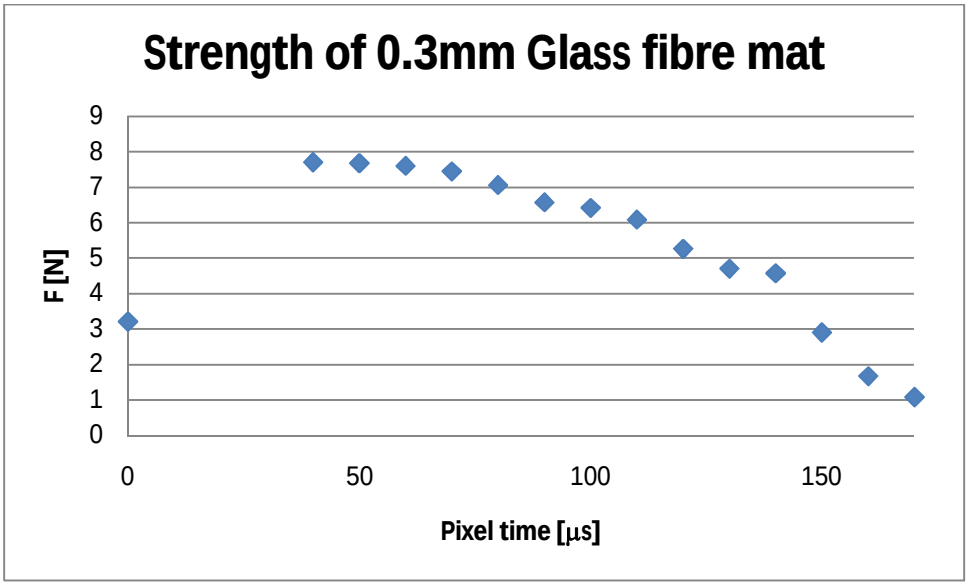

Figure 9 : the laser treated glass fibre mat (0.3mm thick) strength values are greater than the non-treated sample but decreases as the intensity of the laser light beam increases.

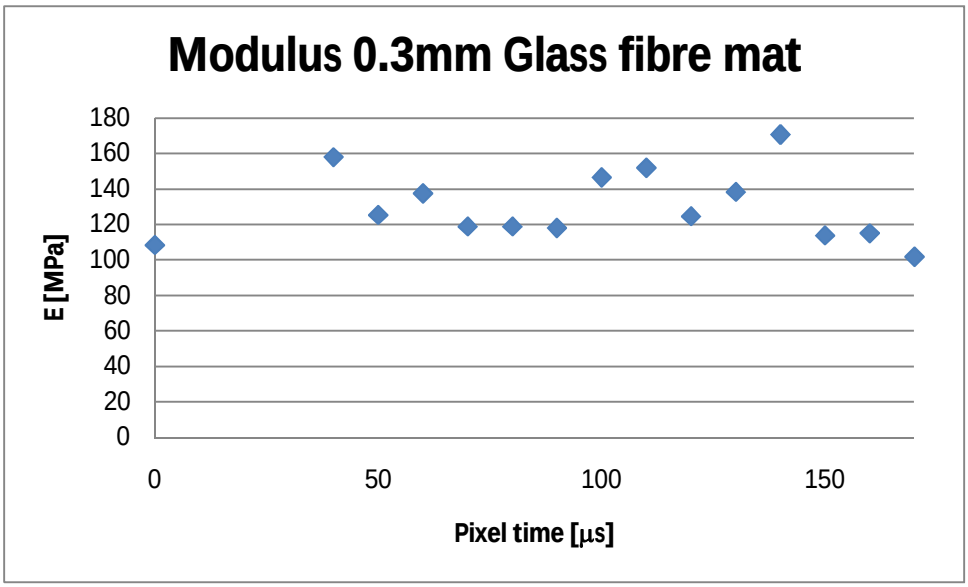

Figure 10 : the modulus values of the laser treated glass fibre (0.3mm thick) are constant as the intensity of the laser light increases, but are greater than the non treated sample.

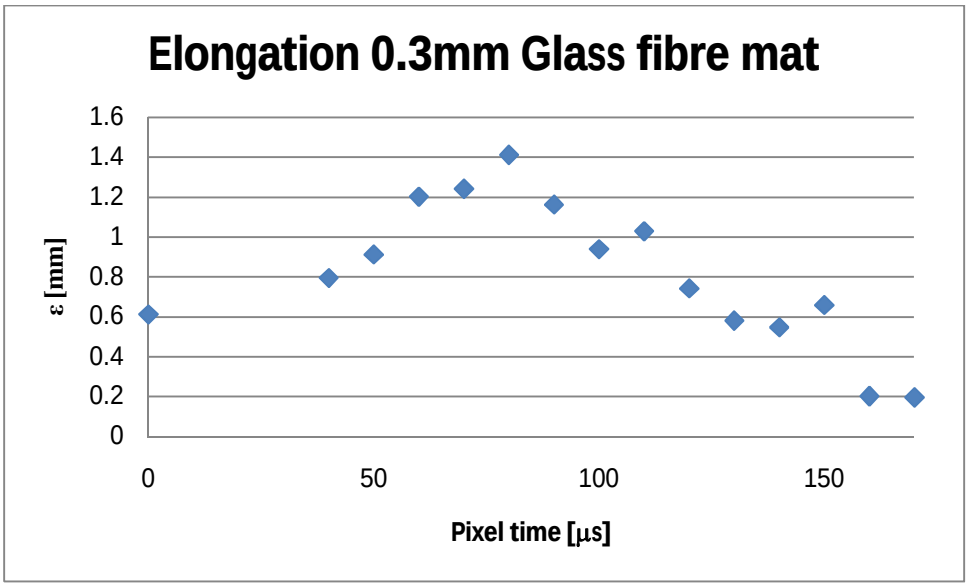

Figure 11 : the elongation of the laser treated glass fibre mat (0.3mm thick) initially increase and it then decreases as the intensity of the laser light increases further.

The treatment of the 0.3mm glass fibre mat produced a glass fibre mat that had greater mechanical properties compared to the untreated glass fibre mat of the same dimensional characteristics. Treating the glass fibre mat with lower intensities, lower being the lowest values used in this treatment, of laser beams produced glass fibres that had greater mechanical properties, but as the intensity of the laser beam increased the mechanical properties decreased. The modulus of the material remained almost constant throughout the treatment.

3.1.2. Laser light beam cycle treatment

The glass fibre mat was treated at a constant intensity of laser light beam and the number of cycles was varied. The 1.6mm glass fibre mat was treated at an intensity of 100μs pixel time, and the 0.3mm glass fibre mat was treated at an intensity of 40μs pixel time.

Table 5 : Tira Test 2300, mechanical parameters of the 1.6mm thick nonwoven glass fibre structure which was irradiated with a carbon dioxide laser beam, with an intensity of 100μs pixel time at different cycle intervals. The glass fibre mat structure was the stretched at a rate of 50mm/min.

Number of Cycles	F [N]	E [MPa]	ε [mm]
0	25.66	44.61	3.67
2	26.40	78.99	3.99
3	26.84	81.13	4.28
4	28.15	83.60	4.31
5	29.49	79.26	4.77
6	28.20	83.49	3.33
7	26.35	72.32	3.27

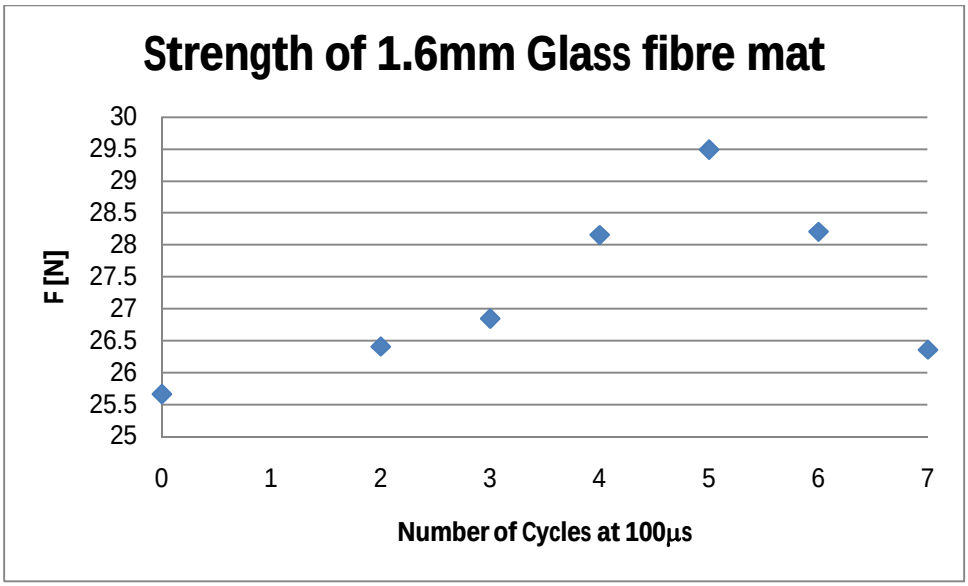

Figure 12 : strength of the 1.6mm glass fibre mat increases then decrease as the number of cycles of the carbon dioxide laser beam increases.

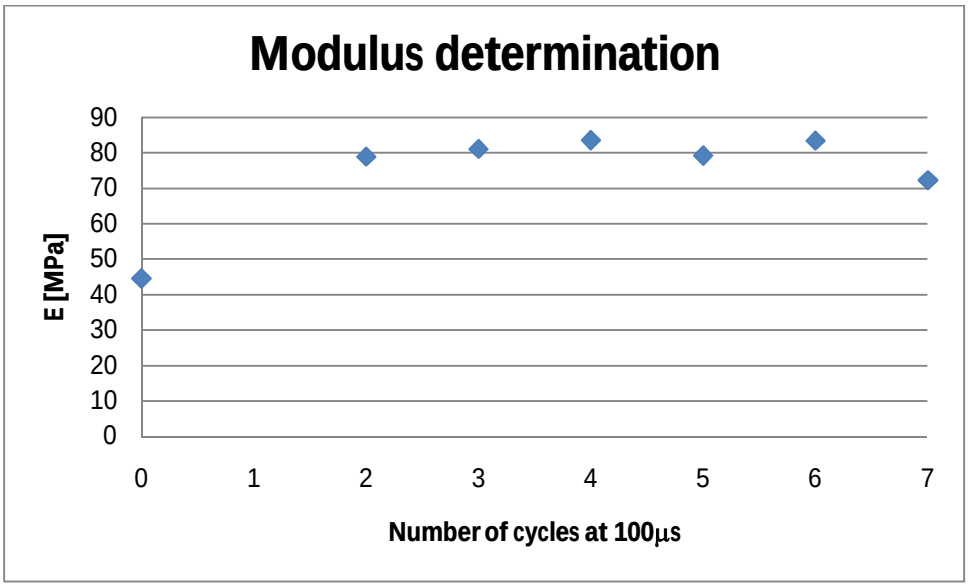

Figure 13 : modulus of the 1.6mm glass fibre is constant with the treatment of a carbon dioxide laser beam, but greater than the non-treated glass fibre mat.

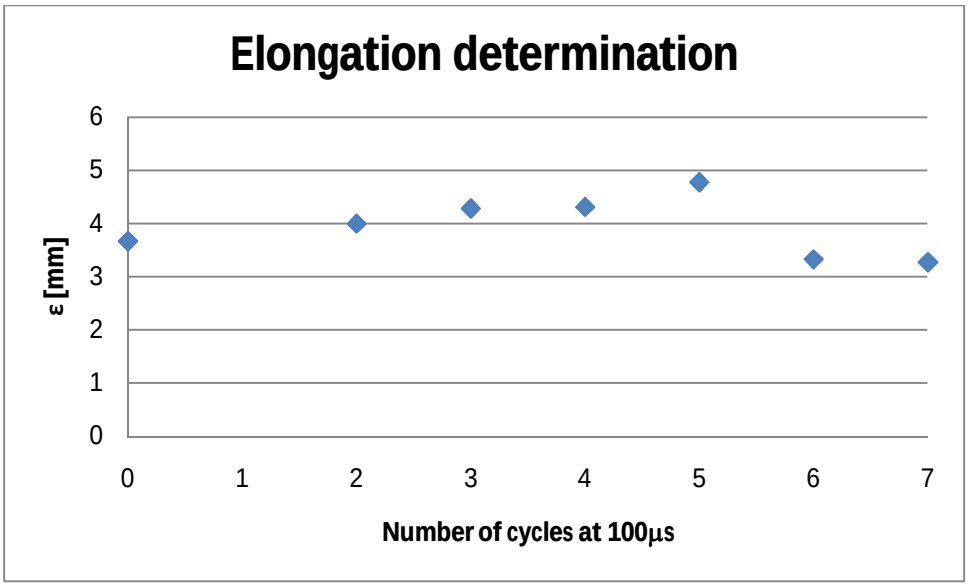

Figure 14 : the elongation of the 1.6mm glass fibre mat is constant when it is treated with a carbon dioxide laser beam.

As the number of laser treatment cycles increased so did the mechanical properties of the treated glass fibre mat compared to the non-treated samples, but the elongation of the samples was almost constant throughout the treatment.

Table 6 : Tira Test 2300, mechanical parameters of a 0.3mm thick nonwoven glass fibre structure which was irradiated with a carbon dioxide laser beam, with an intensity of 40µs pixel time at different cycle intervals. The glass fibre mat structure was the stretched at a rate of 25mm/min.

Number of Cycles	F [N]	E [MPa]	ε [mm]
0	2.83	107.1	1.52
2	3.03	127.41	1.03
3	3.73	126.58	1.12
4	2.25	84.66	0.72
5	3.01	112.88	0.96
6	3.39	112.94	1.03
7	3.24	113.37	0.96

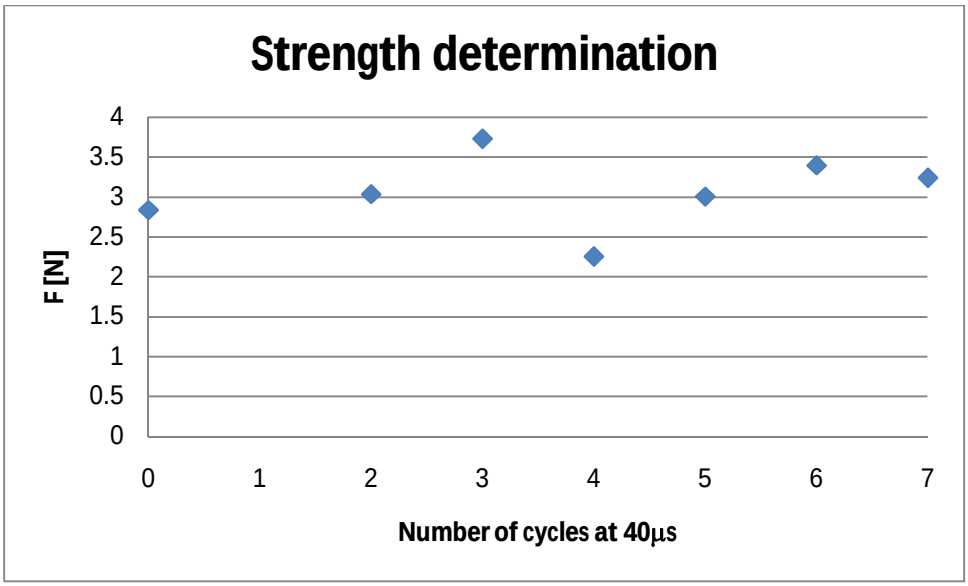

Figure 15 : strength of the 0.3mm glass fibre mat treated with a carbon dioxide laser beam, has strength values that are constant as the number of laser beam treatment cycles increase.

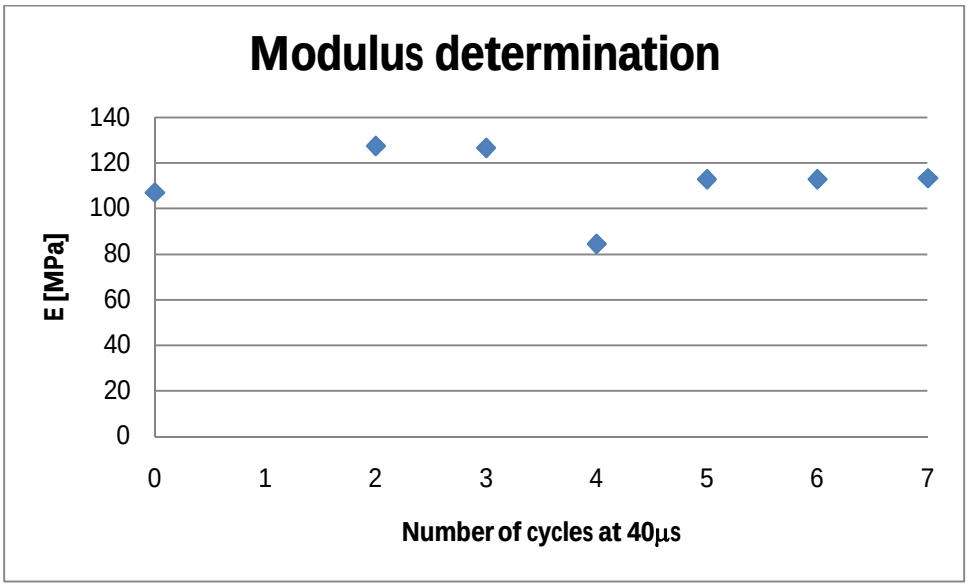

Figure 16 : modulus of the 0.3mm glass fibre mat treated with a carbon dioxide laser beam, has modulus values that are constant as the number of laser beam treatment cycles increase.

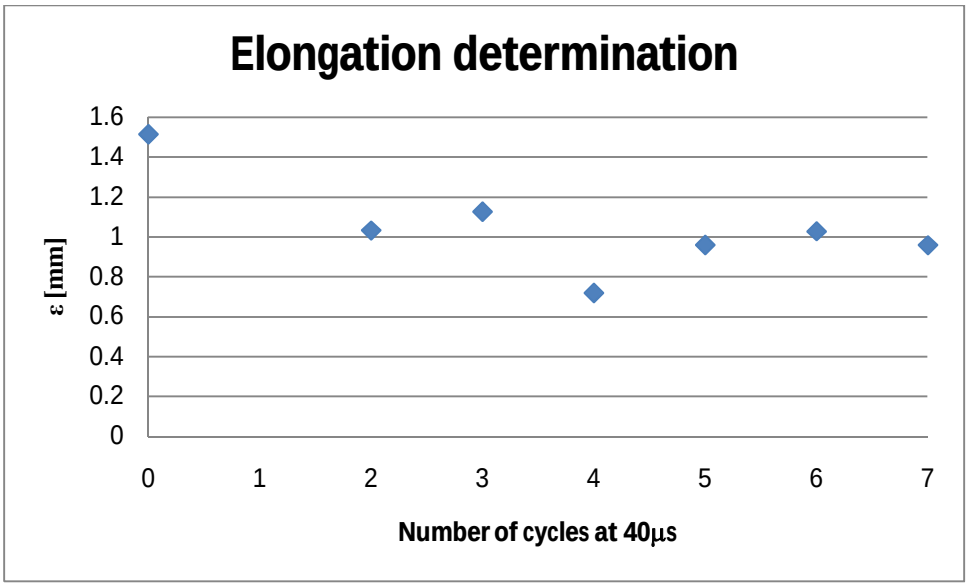

Figure 17 : elongation of the 0.3mm glass fibre mat treated with a carbon dioxide laser beam, has elongation values that are constant but lower than the non treated sample as the number of laser beam treatment cycles increase.

The treatment of the 0.3mm glass fibre mat at increasing number of cycles produced almost constant results, except for the elongation parameters which showed a slight decrease.

3.2. INFRARED THERMOMETER HEAT DETERMINATION OF LASER TREATED OF GLASS FIBRE MAT

The glass fibre mat that was treated with the carbon dioxide laser beam had its temperature determined during treatment. The graphs produced from the treatment show the amount of heat temperature on the glass fibre mat during carbon dioxide laser light treatment. The amount of peaks represents the number of laser beam cycle treatments. The tip of the peaks is the maximum temperature experienced by the glass fibre mat.

The laser treatment temperature was determined for the lowest temperature that was used. This temperature was enough to cause a noticeable effect on the glass fibre mat. The temperature was

determined during the laser cycle treatment of both the thick (1.6mm irradiated at 100µs pixel time) and the thin (0.3mm irradiated at 40µs pixel time) glass fibre mat samples.

Table 7 : maximum and minimum temperature of the glass fibre mat during laser cycle treatment on glass fibre mat

Sample Thickness Size [mm]	**T_{min} [^oC]**	**T_{max} [^oC]**
0.3	220	440
1.6	305	500

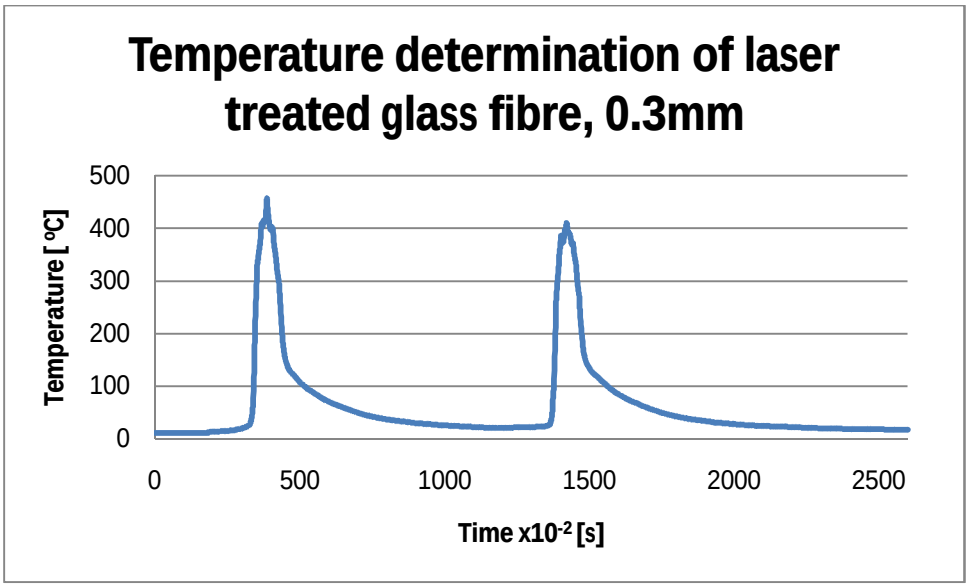

Figure 18 : 0.3mm glass fibre mat irradiated twice (2 cycles) at 40µs pixel time.

3.3. PERMEABILITY OF GLASS FIBRE MAT

The 1.6mm and 0.3mm thick glass fibre mat samples that were treated at increasing laser beam intensities and increasing number of laser beam cycles were tested for air permeability at a pressure of 200Pa.

Table 8 : permeability parameters for glass fibre mat treated by laser light beam; 0.3mm thick sample and a 1.6mm thick sample. The 0.3mm thick sample was treated at 40µs pixel time and the number of treatment cycles varied according to the values indicated in the table. The 1.6mm thick sample was treated with 100µs pixel time for and the number of treatment cycles varied according to the values indicated in the table.

Sample	**Number of Laser treatment cycles**	**Permeability of 0.3mm** $[l/m^2/s]$	**Permeability of 1.6mm** $[l/m^2/s]$
Standard sample	0	90.50	14.50
1	1	92.00	15.20
2	2	94.00	15.80
3	3	93.00	16.00
4	4	94.40	16.30
5	5	93.40	16.70
6	6	93.50	16.90
7	7	93.30	17.20
8	8	96.40	17.10

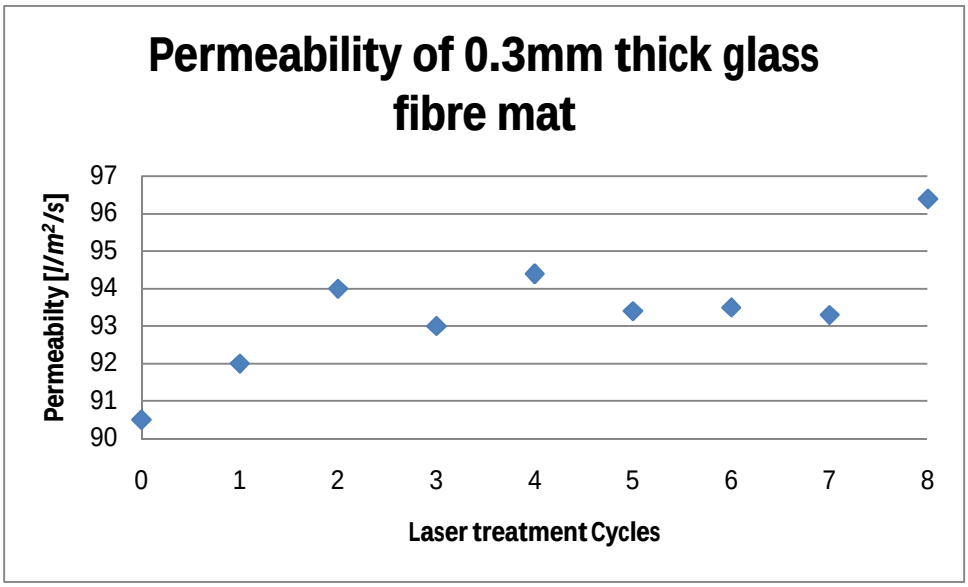

Figure 19 : the permeability of the 0.3mm glass fibre mat, treated with a carbon dioxide laser beam at 40µs pixel time at varying cycles, has air permeability values that increase as the number of laser beam cycles increase.

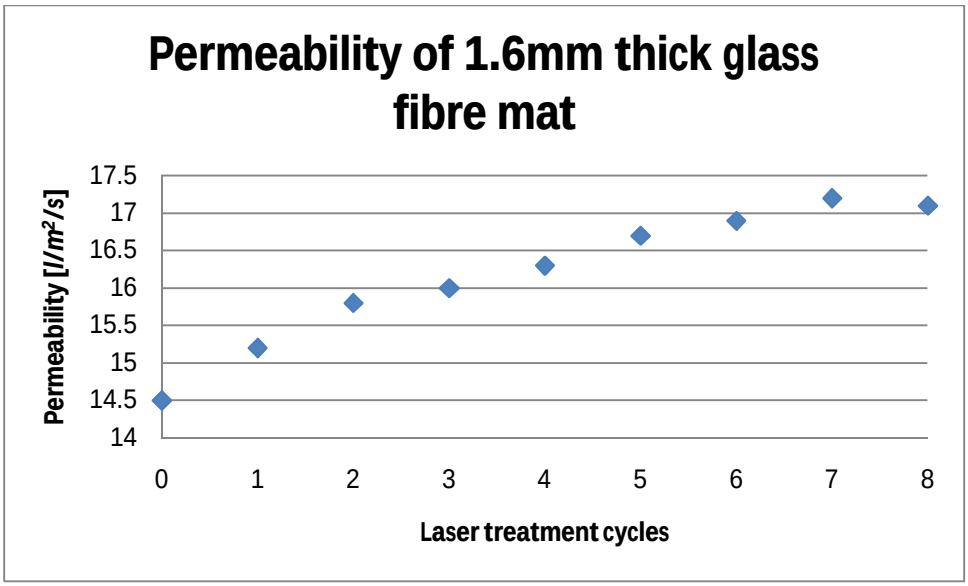

Figure 20 : the permeability of the 1.6mm glass fibre mat, treated with a carbon dioxide laser beam at 100µs pixel time at varying cycles, has air permeability values that increase as the number of laser beam cycles increase.

Table 9 : permeability parameters for the 0.3mm thick glass fibre mat treated with a laser light beam.

Sample	**Pixel time** **[µs]**	**Permeability** **[$l/m^2/s$]**
Standard sample	0	90.50
1	40	92.10
2	80	99.30
3	100	108
4	120	114
5	140	114
6	160	126
7	200	135
8	240	185

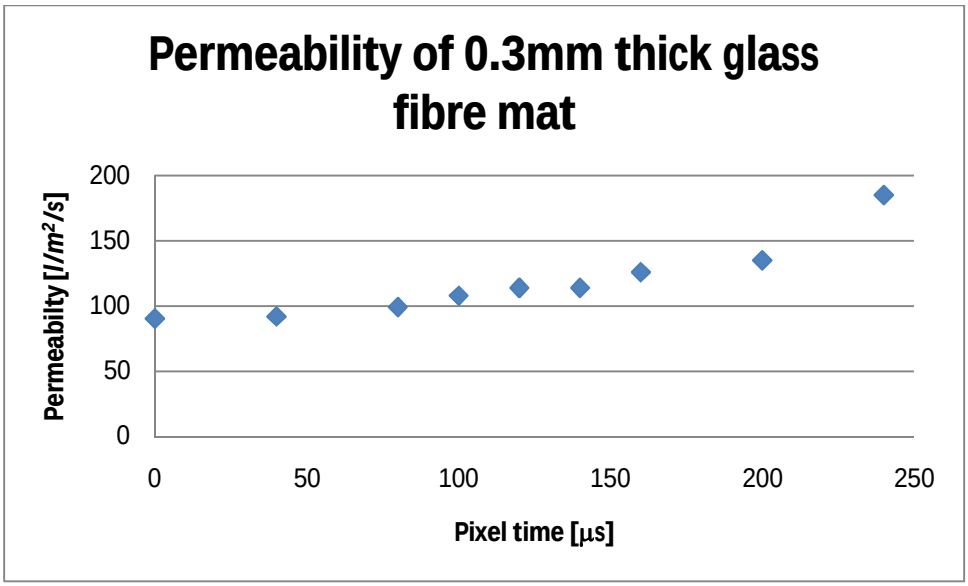

Figure 21 : the permeability of the 0.3mm glass fibre mat, treated with a carbon dioxide laser beam, has permeability values that increase as the laser beam intensity increases.

Table 10 : permeability parameters for the 1.6mm glass fibre treated by laser light.

Sample	**Pixel time** **[µs]**	**Permeability** **[$l/m^2/s$]**
Standard	0	14.50
1	100	15.40
2	200	16.40
3	300	17.80
4	400	18.80
5	500	20.50
6	600	23.00
7	700	25.40
8	800	27.80

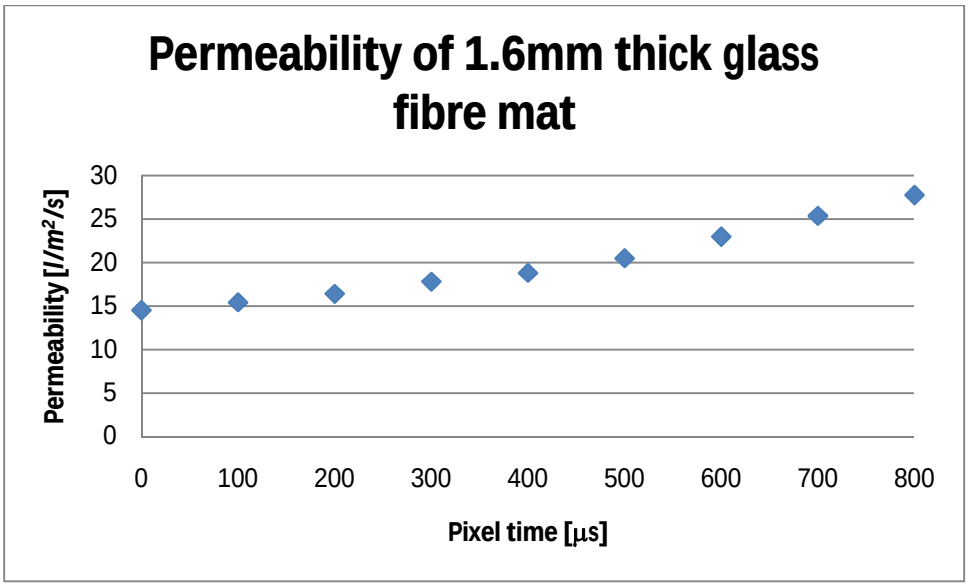

Figure 22 : the permeability of the 1.6mm glass fibre mat, treated with a carbon dioxide laser beam, has permeability values that increase as the laser beam intensity increases.

As shown in the graphs above the air permeability of the glass fibre mats increase as the amount of laser light intensity increase and also as the number of laser treatment cycles increases.

3.4. THICKNESS OF GLASS FIBRE MAT

The 1.6mm and 0.3mm glass fibre mat samples that were treated at increasing laser beam intensities and increasing number of laser beam cycles were tested for thickness parameters. The samples were tested at three different pressures, with a test area of 1000mm^2.

Table 11 : 1.6mm thick glass fibre mat thickness parameters at different pressure levels, after laser light beam treatment

Pixel time [µs]	Average Thickness at 0.1kPa [mm]	Average Thickness at 1.0kPa [mm]	Average Thickness at 50kPa [mm]
0.00	2.02	1.85	1.48
100	1.85	1.77	1.42
200	1.76	1.68	1.34
300	1.74	1.61	1.29
400	1.64	1.52	1.24
500	1.61	1.48	1.20
600	1.68	1.41	1.14
700	1.49	1.28	1.06
800	1.33	1.21	1.01

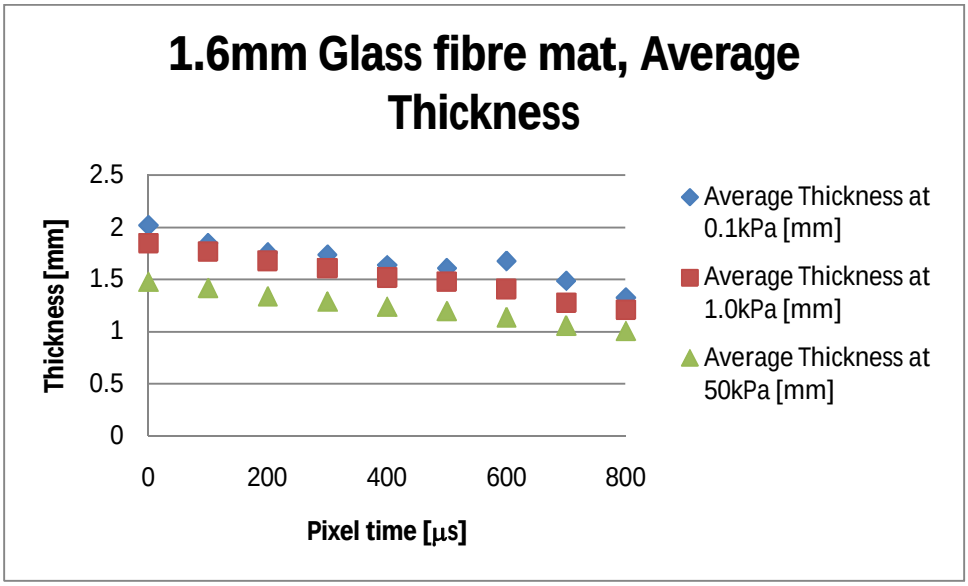

Figure 23 : 1.6mm glass fibre mat treated at increasing laser beam intensities with thickness determined at different pressure levels

Table 12 : 0.3mm thick glass fibre mat thickness parameters at different pressure levels, after laser light beam treatment

Pixel time [µs]	Average Thickness at 0.1kPa [mm]	Average Thickness at 1.0kPa [mm]	Average Thickness at 50kPa [mm]
0	0.49	0.42	0.32
40	0.50	0.40	0.32
80	0.48	0.40	0.32
100	0.46	0.37	0.30
120	0.45	0.35	0.28
140	0.43	0.35	0.28
160	0.40	0.32	0.26
200	0.41	0.31	0.26
240	0.34	0.25	0.22

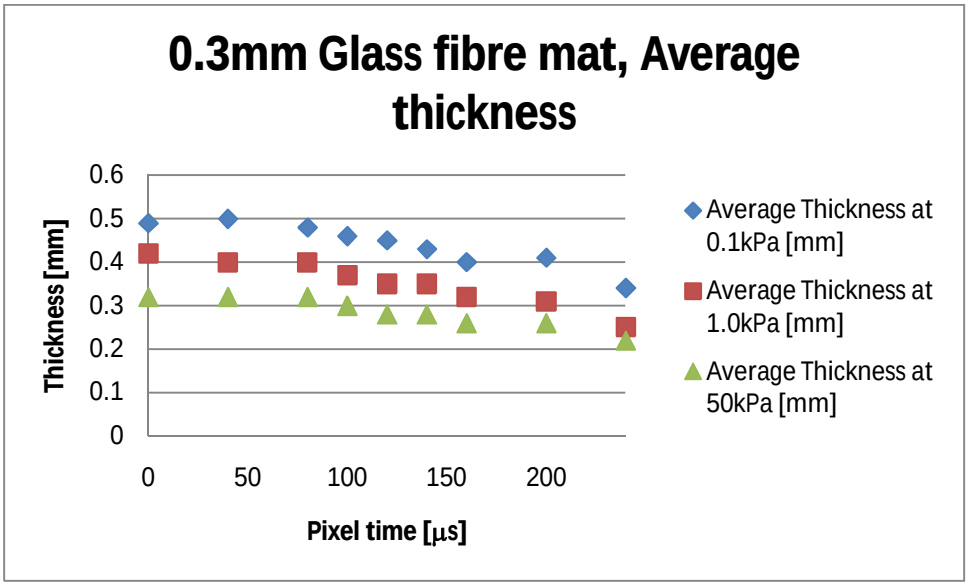

Figure 24: 0.3mm glass fibre mat treated at increasing laser beam intensities with thickness determined at different pressure levels

Table 13 : 1.6mm thick glass fibre mat thickness parameters at different pressure levels, after laser light beam treatment.

Number of Pixel time cycles	Average Thickness at 0.1kPa [mm]	Average Thickness at 1.0kPa [mm]	Average Thickness at 50kPa [mm]
0	2.00	1.85	1.46
1	1.84	1.75	1.41
2	1.88	1.78	1.42
3	1.88	1.77	1.42
4	1.87	1.77	1.41
5	1.85	1.74	1.41
6	1.86	1.77	1.41
7	1.87	1.78	1.42
8	1.86	1.77	1.37

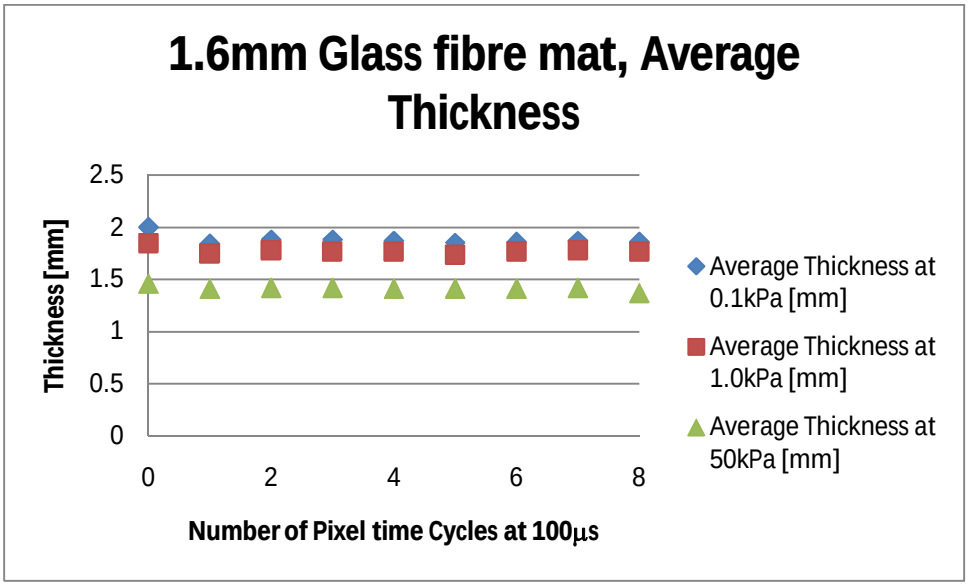

Figure 25 : 1.6mm glass fibre mat treated at increasing laser beam intensities with thickness determined at different pressure level

Table 14 : 0.3mm thick glass fibre mat thickness parameters at different pressure levels, after laser light beam treatment

Number of Pixel time cycles	Average Thickness at 0.1kPa [mm]	Average Thickness at 1.0kPa [mm]	Average Thickness at 50kPa [mm]
0	0.47	0.42	0.31
1	0.46	0.42	0.31
2	0.48	0.43	0.31
3	0.46	0.43	0.31
4	0.45	0.42	0.31
5	0.45	0.40	0.30
6	0.44	0.40	0.31
7	0.46	0.40	0.31
8	0.45	0.40	0.31

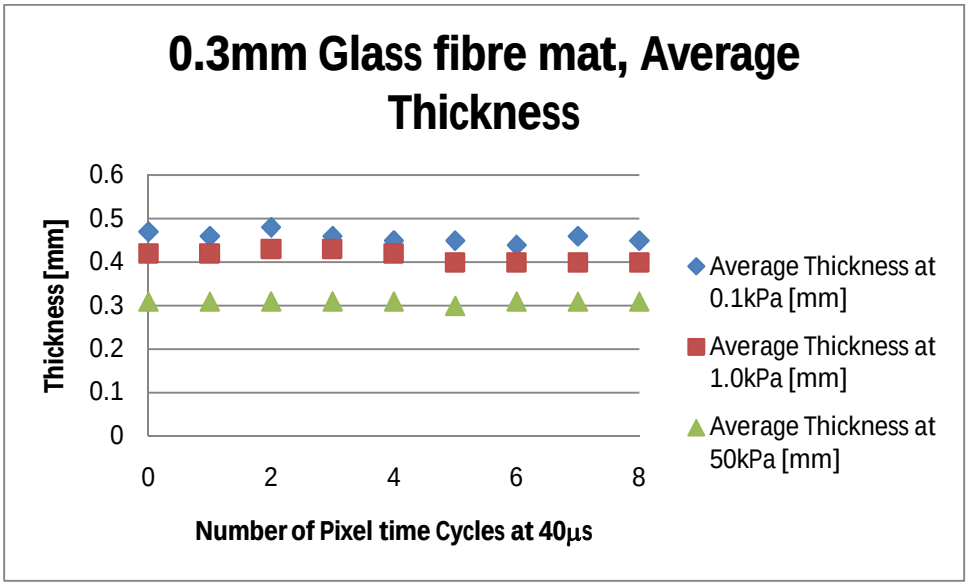

Figure 26 : 0.3mm glass fibre mat treated at increasing laser beam intensities with thickness determined at different pressure levels

3.5. SCANNING ELCTRON MICROSCOPE IMAGES OF TREATED GLASS FIBRE MAT

3.5.1. Scanning Electron microscope images of the 1.6mm thick glass fibre mats treated with increasing laser beam intensities.

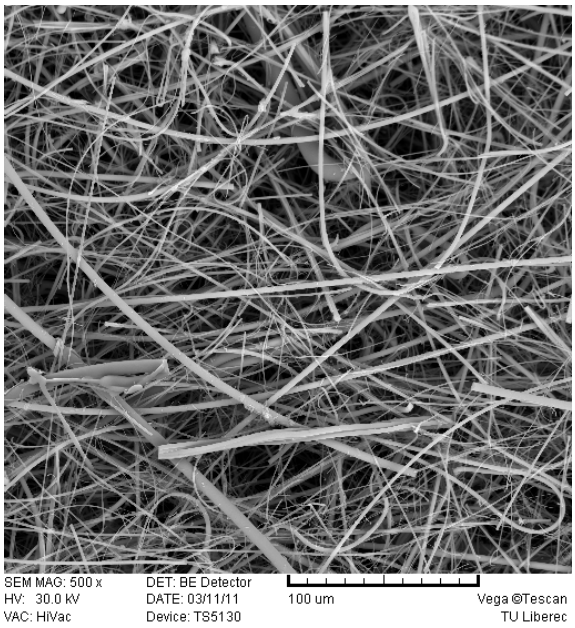

Figure 27 : 0µs pixel time laser beam intensity

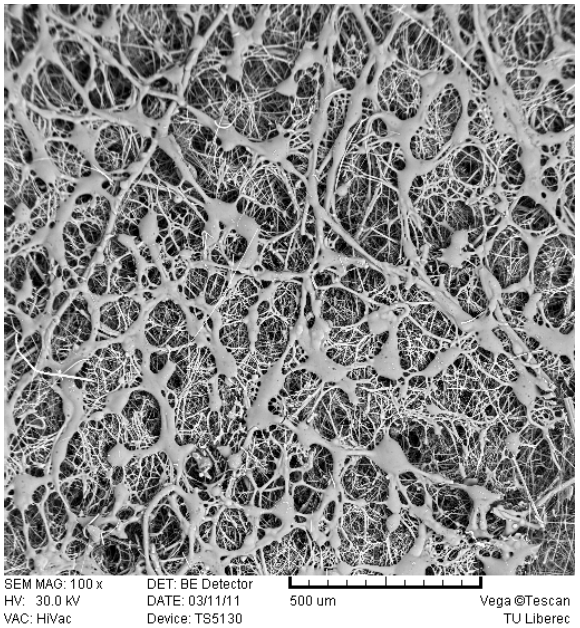

Figure 28 : 100µs laser beam intensity

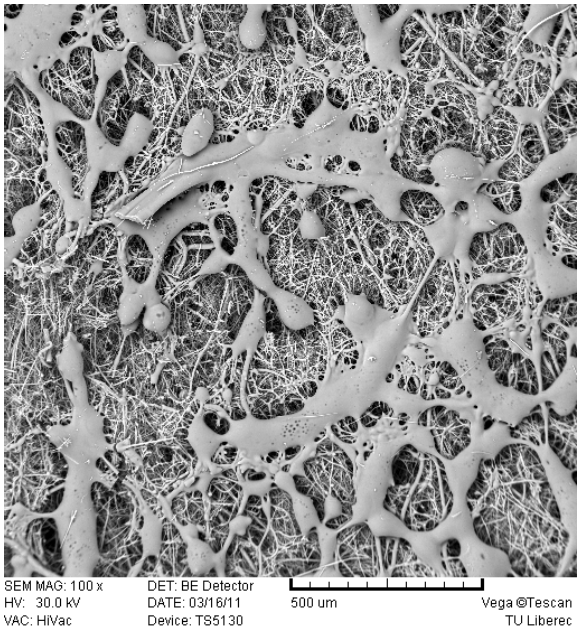

Figure 29 : 200µs laser beam intensity

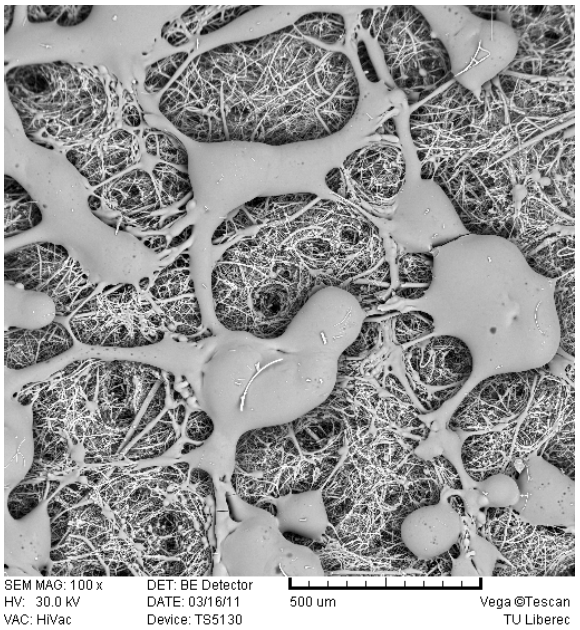

Figure 30 : 300µs laser beam intensity

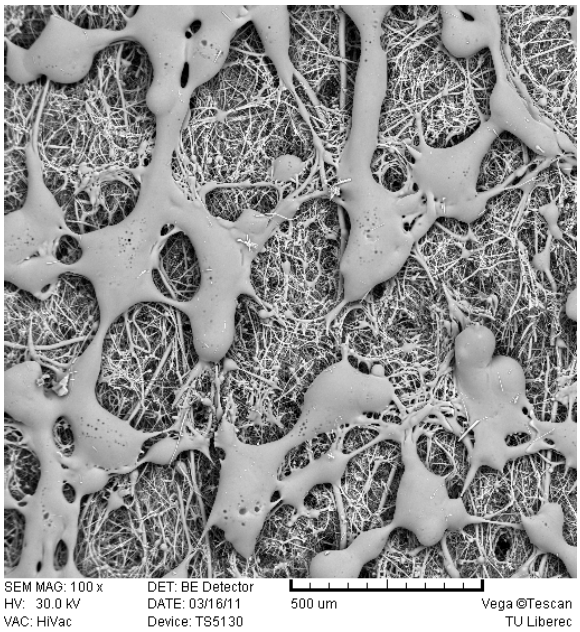

Figure 31 : 400µs laser beam intensity

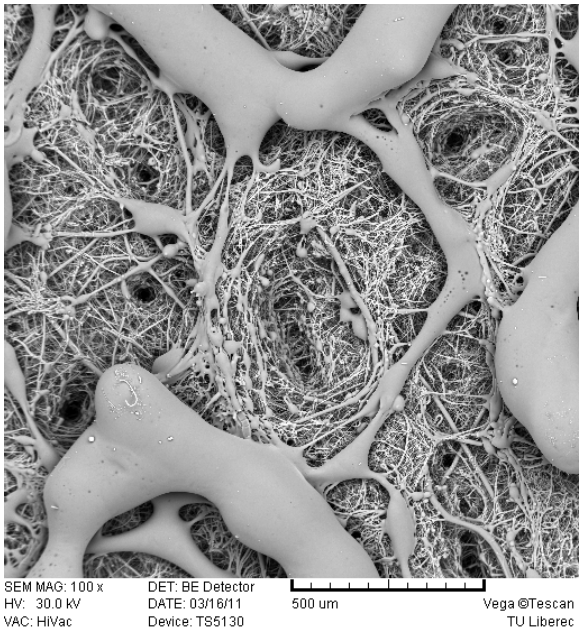

Figure 32 : 600µs laser beam intensity

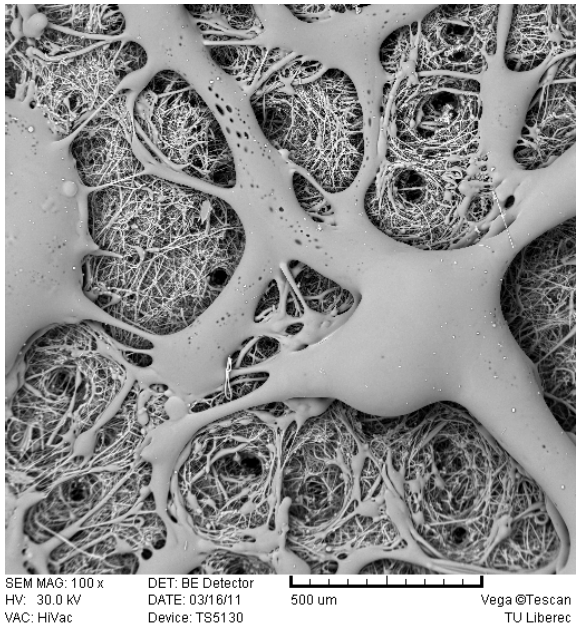

Figure 33 : 800µs laser beam intensity

The figures above display the glass fibre mats that were treated with the carbon dioxide laser beam at increasing light beam intensities. It is noted that as the intensity of the light beam

increases so does the melted parts of the glass fibre. The laser light beam melts the glass fibres and creates bonding spots which are very much greater than the fibres themselves.

3.5.2. Scanning Electron Microscope images of 0.3mm glass fibre mat treated with a carbon dioxide laser beam at increasing beam intensities.

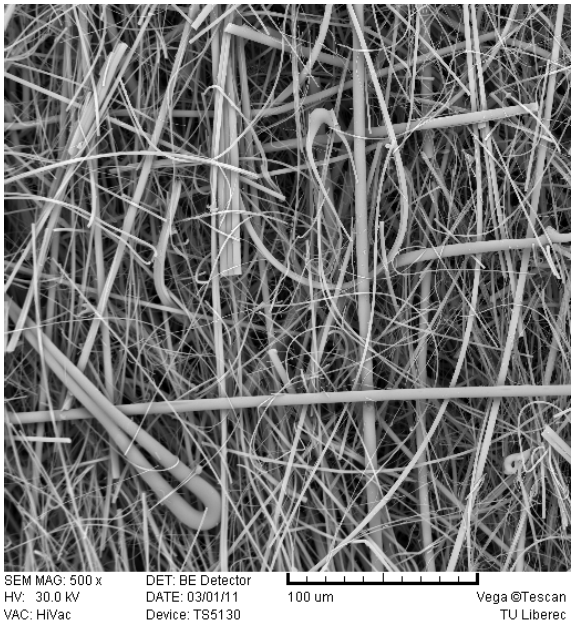

Figure 34 : 0μs laser beam intensity

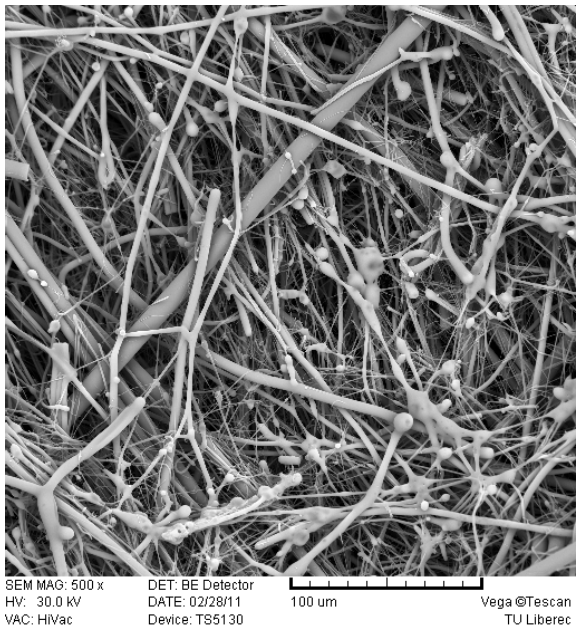

Figure 35 : 40μs laser beam intensity

Figure 36 : 60µs laser beam intensity

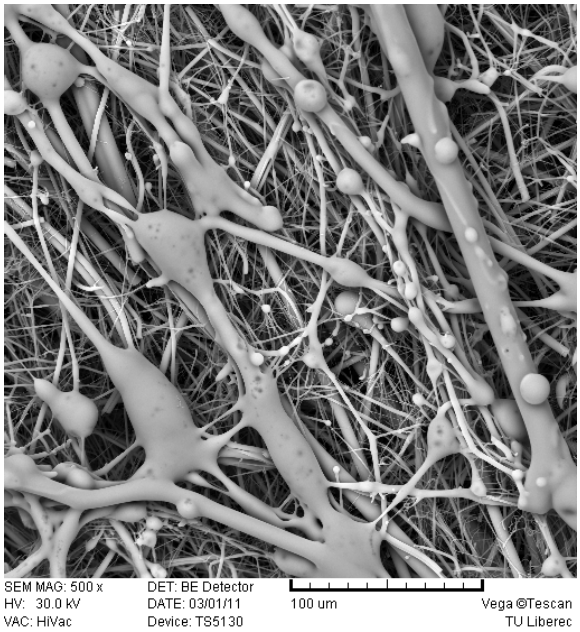

Figure 37 : 80µs laser beam intensity

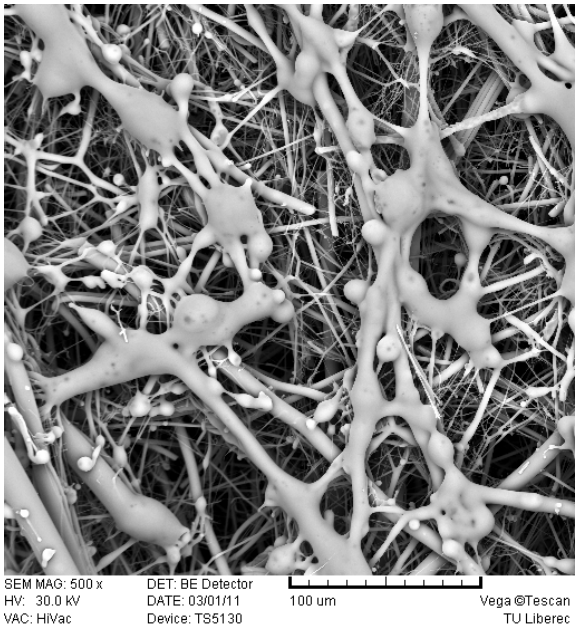

Figure 38 : 100µs laser beam intensity

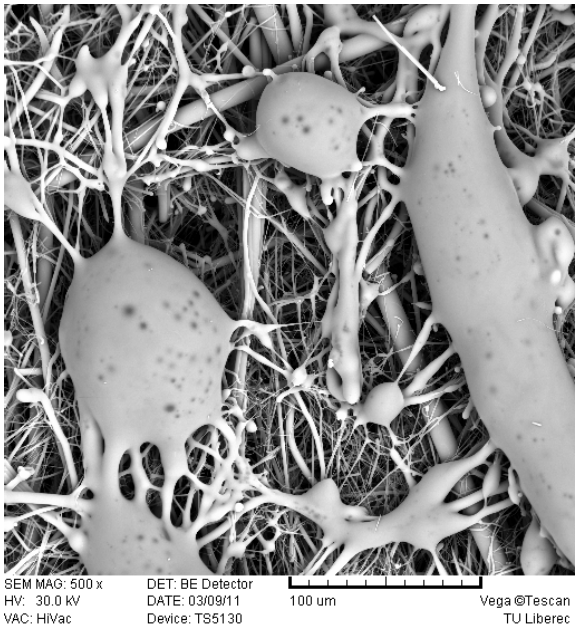

Figure 39 : 120µs laser beam intensity

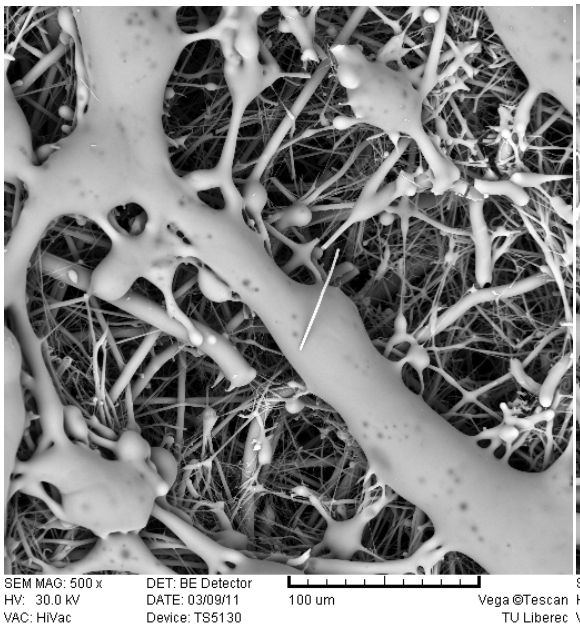

Figure 40 : 160µs laser beam intensity

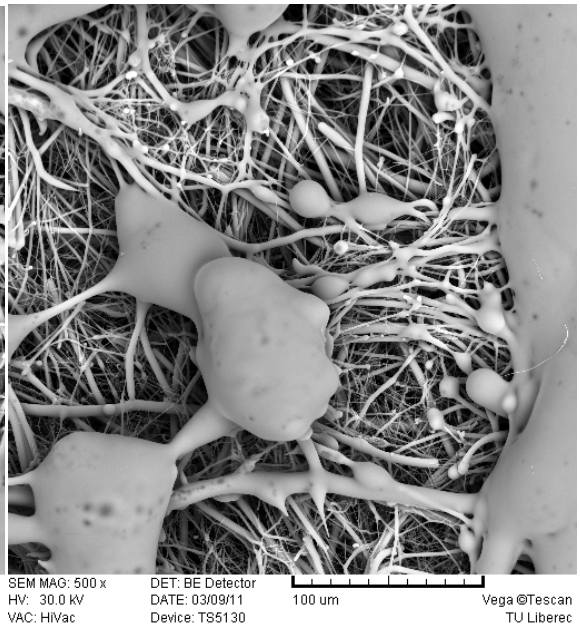

Figure 41 : 200µs laser beam intensity

The figures above display the glass fibre mats that were treated with the carbon dioxide laser beam at increasing light beam intensities. It is noted that as the intensity of the light beam increases so does the melted parts of the glass fibre. The laser light beam melts the glass fibres and creates bonding spots which are very much greater than the fibres themselves. The fibre ends form spherical melts which increase in size as the intensity of the laser beam increase.

3.5.3. Scanning electron microscope images of 1.6mm thick glass fibre mat treated at 100µs at increasing number of cycles.

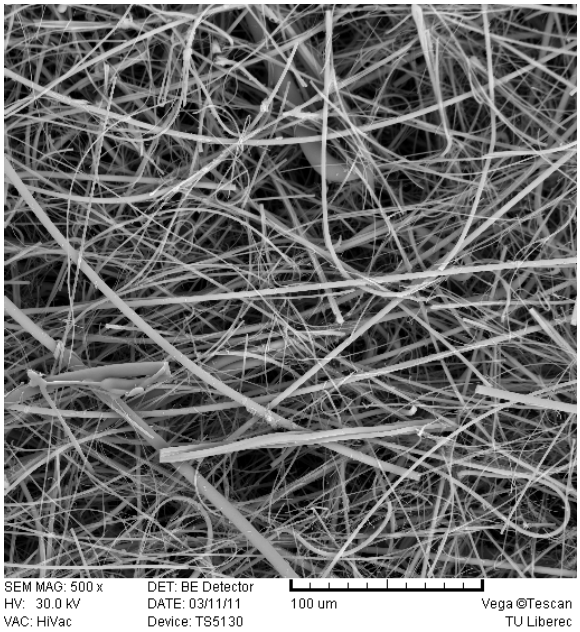

Figure 42 : 0µs, no treatment

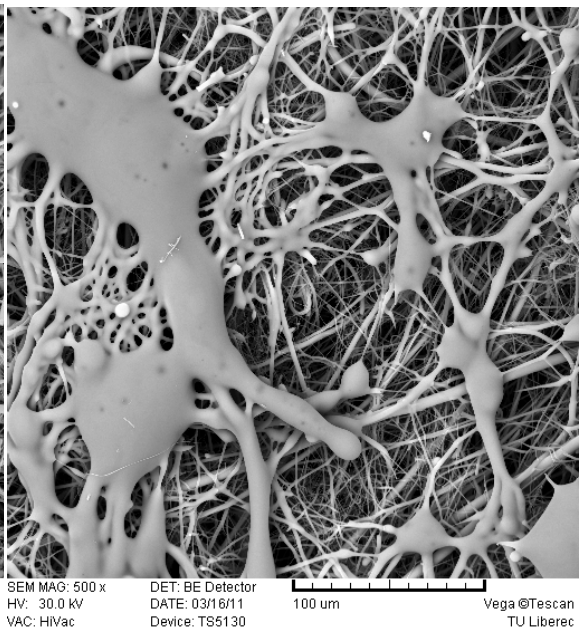

Figure 43 : 100µs treatment, once only

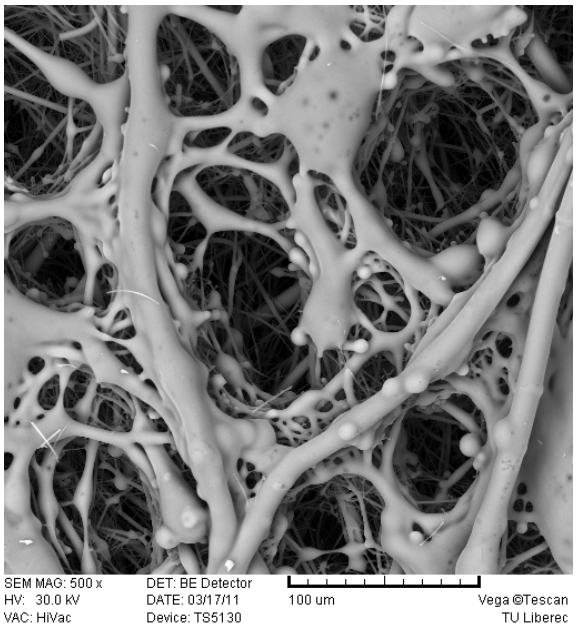

Figure 44 : 100µs treatment, twice

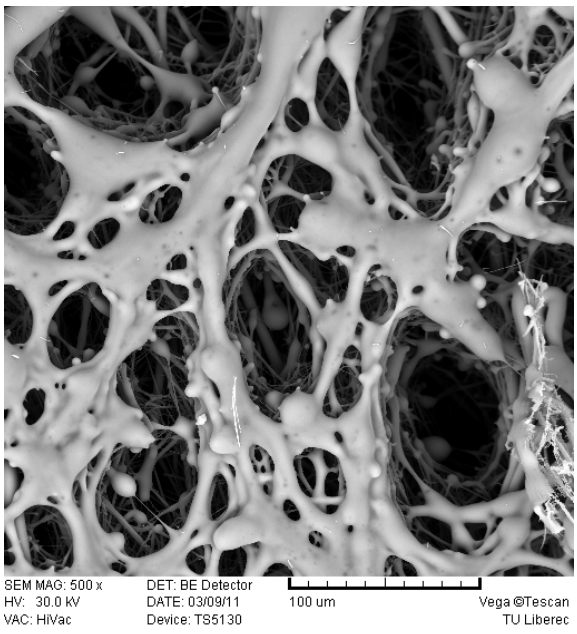

Figure 45 : 100µs treatment, three times

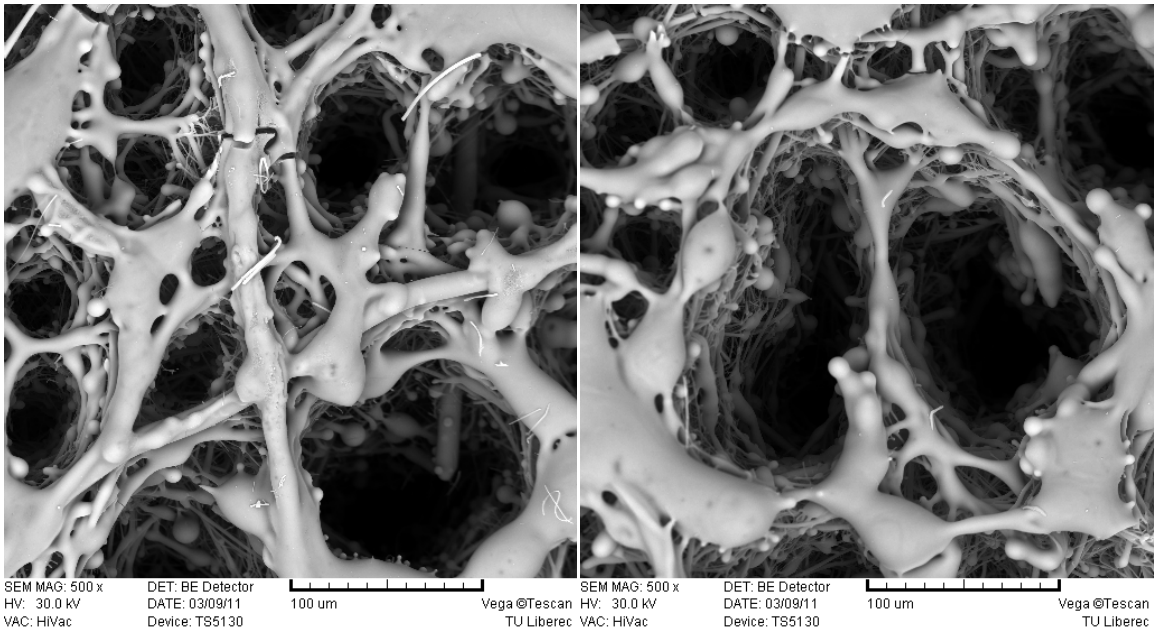

Figure 46 : 100μs treatment, five times Figure 47 : 100μs treatment, seven times

During laser light treatment of the glass fibre mat the glass fibre mat absorbed the heat energy from the laser beam, it heated up and during the process the fibres started to shrink and melt therefore forming fibres with spherical endings. The smaller fibres melted and combined with other melted fibres thus forming a larger solid structure which is very much bigger than the individual fibres themselves. As the fibres melted and combined with other fibres to form a solid structure, spaces were being created. This resulted in greater/bigger pore sized glass fibre mat.

3.5.4. Scanning Electron Microscope images of 0.3mm glass fibre mat treated with a carbon dioxide laser beam intensity of 40μs at increasing number of cycles

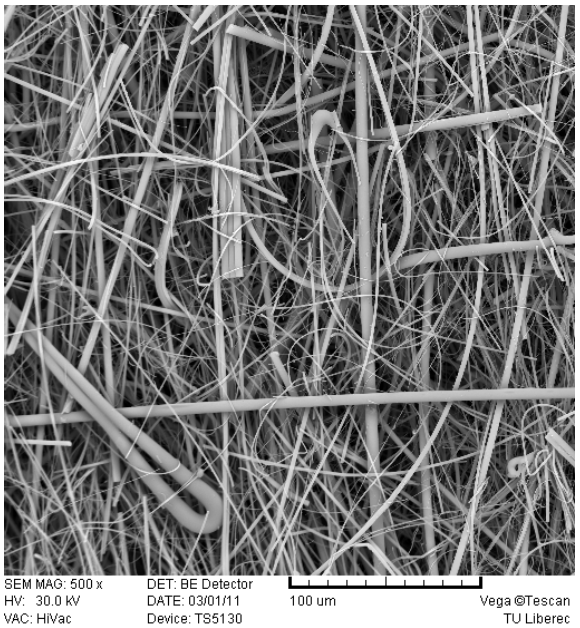

Figure 48 : 0μs, no treatment

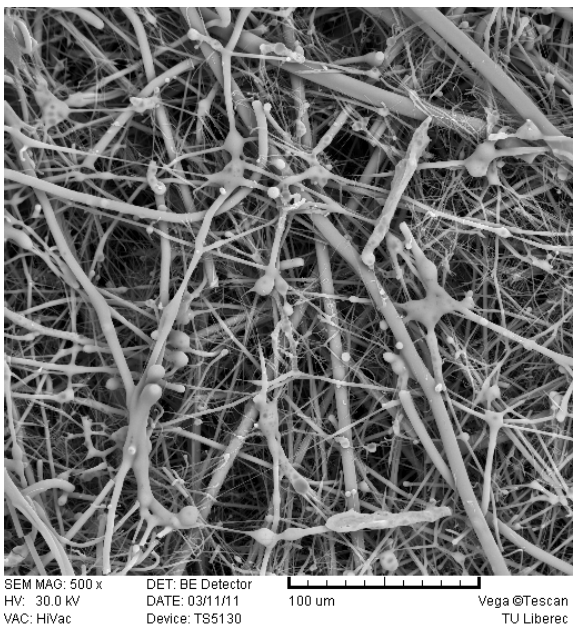

Figure 49 : 40μs treatment, once only

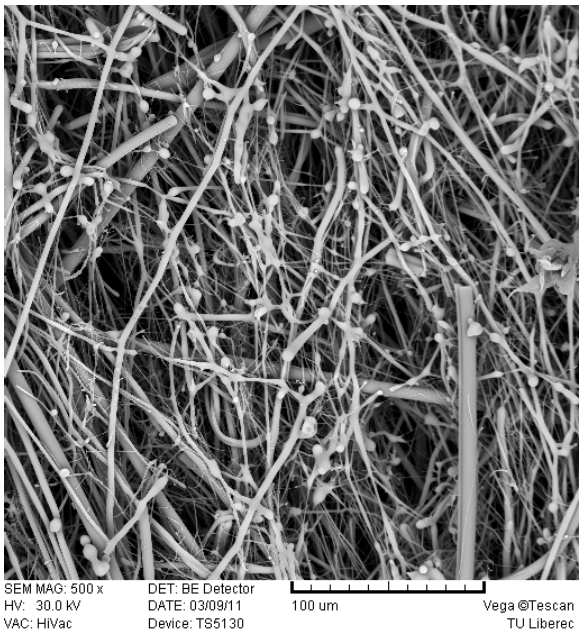

Figure 50 : 40μs treatment, three times

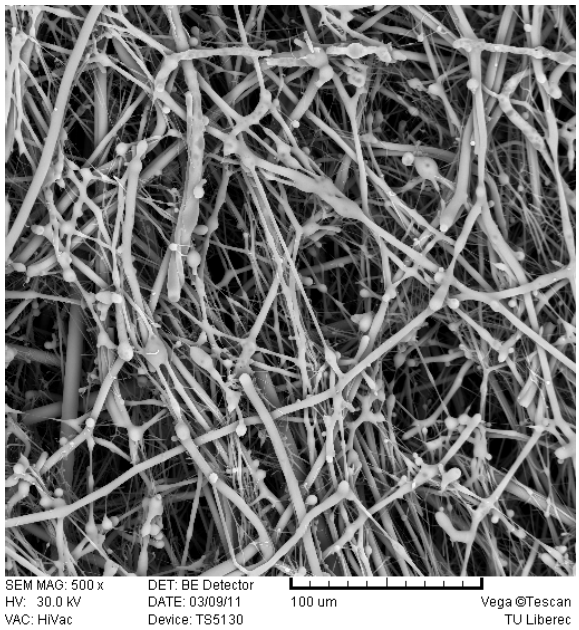

Figure 51 : 40μs treatment, five times

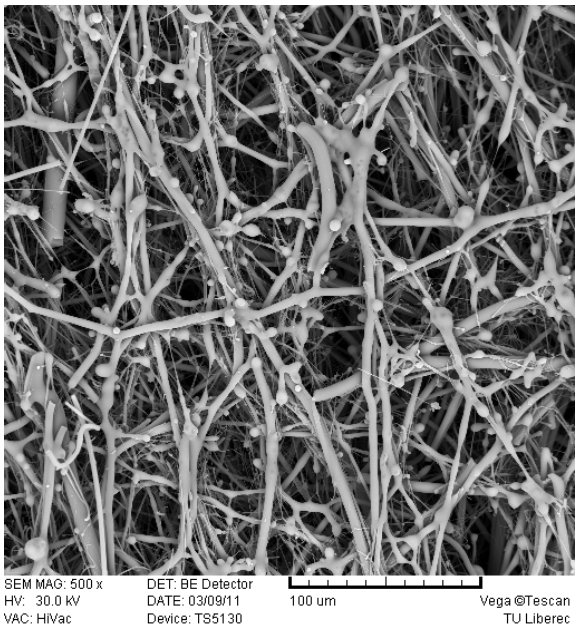

Figure 52 : 40μs treatment, seven times

The thinner 0.3mm glass fibre mat treated at 40μs did not melt as much as the thicker (1.6mm) glass fibre mats because a smaller intensity of laser beam energy was used. The 0.3mm glass fibre mat melted at the end of the fibre and formed mostly spherical endings and did not melt too much to such an extent that the fibres combined to form a bigger than the fibre solid structure. This melting and forming of spherical endings resulted in the creation of greater pore sized glass fibre mat. This occurred because as the spherical endings formed shrinkage in terms of length occurred.

3.6. LASER LIGHT BEAM INCORPORATION OF METALS INTO GLASS FIBRE MAT

Metal oxides may be incorporated into glass fibre mat by laser light beam treatment. This occurred as the glass fibres started to melt around the metal oxide powder. This resulted in the confinement of the metals within the glass fibre as the glass fibre cooled after laser light beam treatment. The highest peaks in the figures below, in the X-ray fluorescence spectra, represent the metal ions that were confined in the glass fibre.

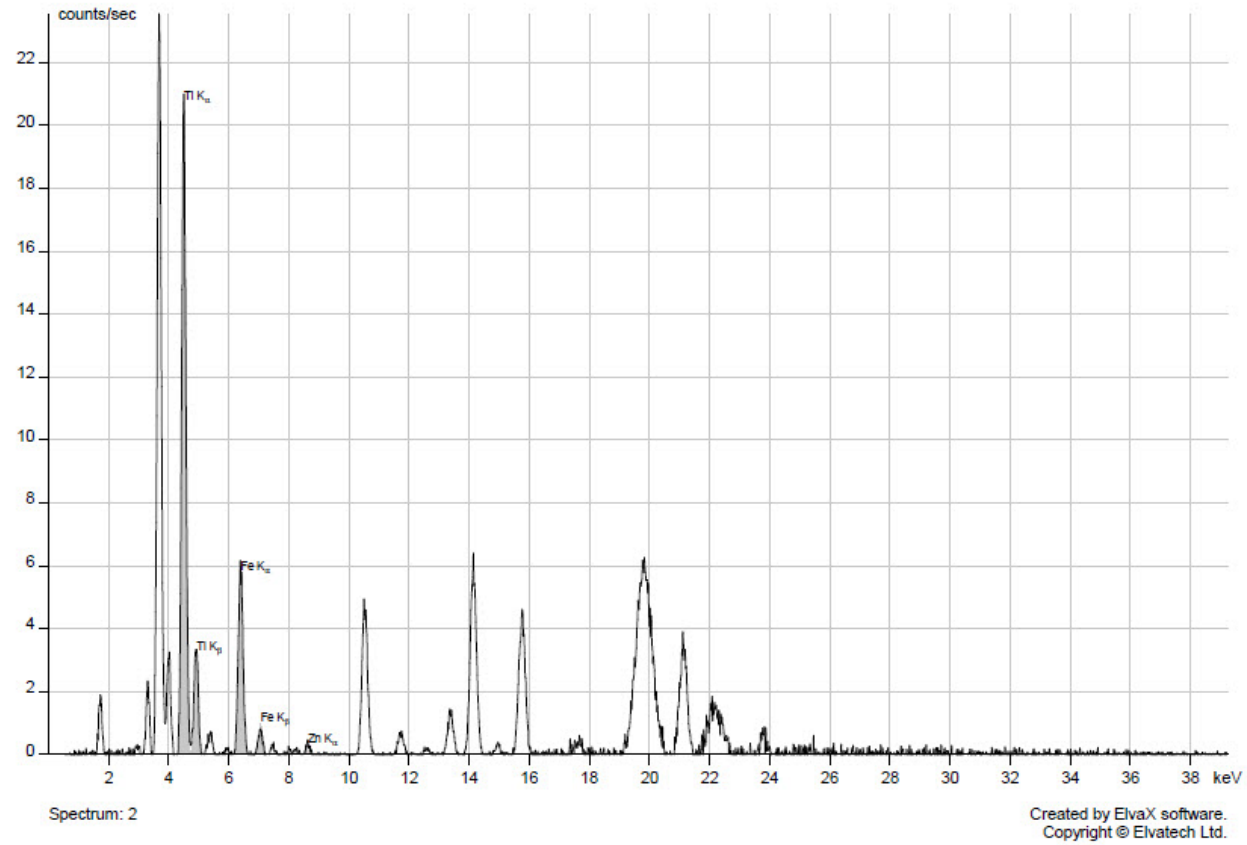

Figure 53 : X-ray fluorescence spectrum view of Titanium metal incorporated into the glass fibre by laser light treatment.

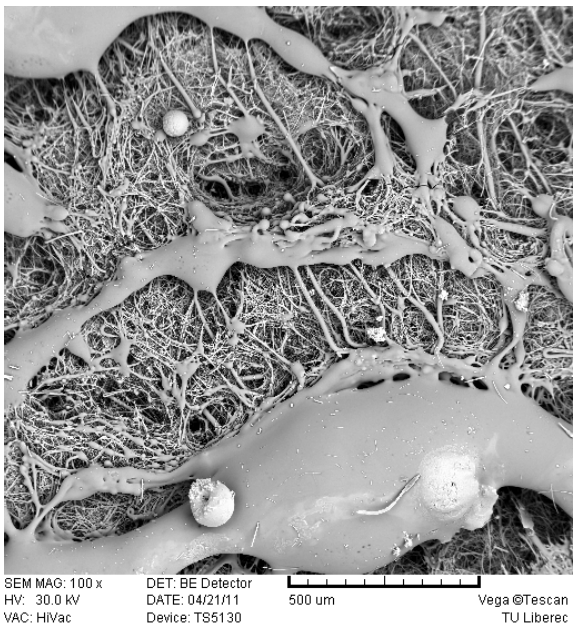

Figure 54 : Titanium particles incorporated into glass fibre mat by laser light treatment.

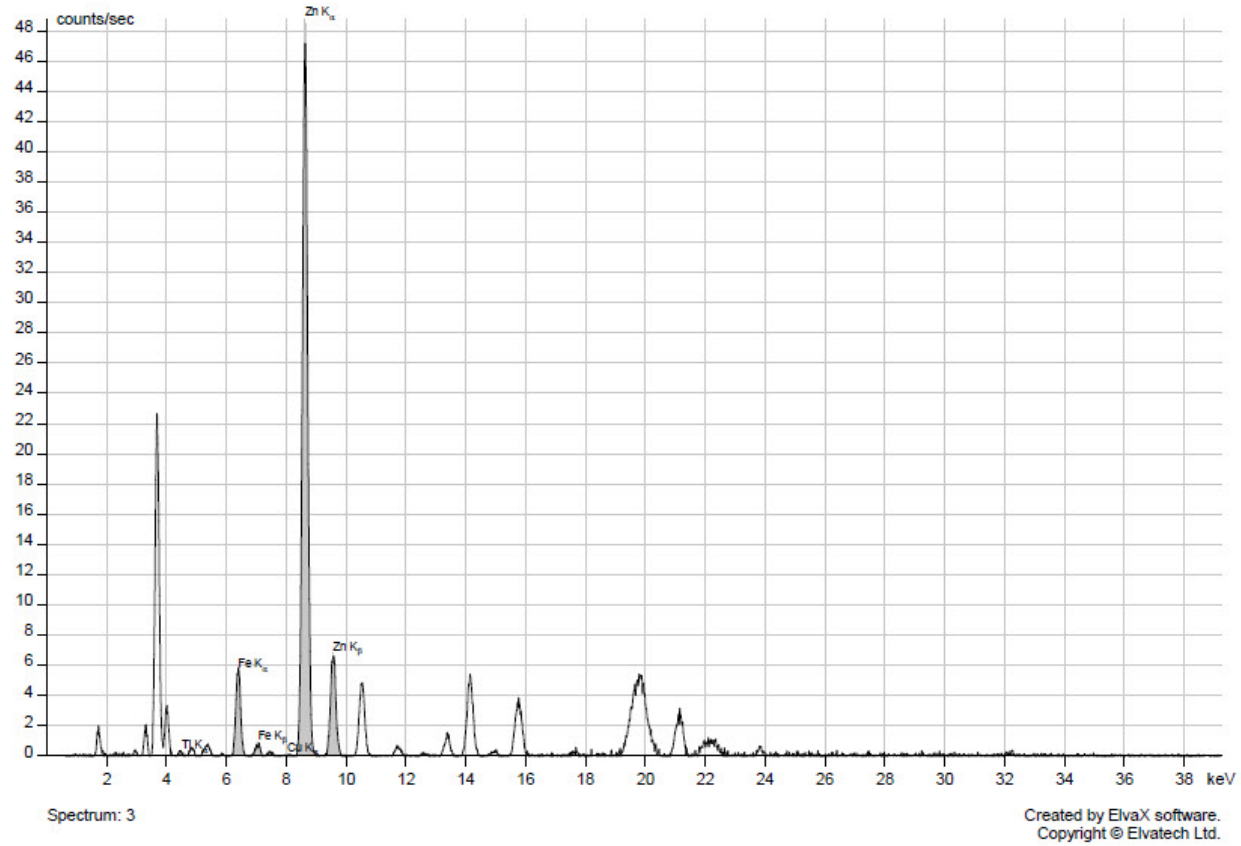

Figure 55 : X-ray fluorescence spectrum view of Zinc metal incorporated into the glass fibre by laser light treatment

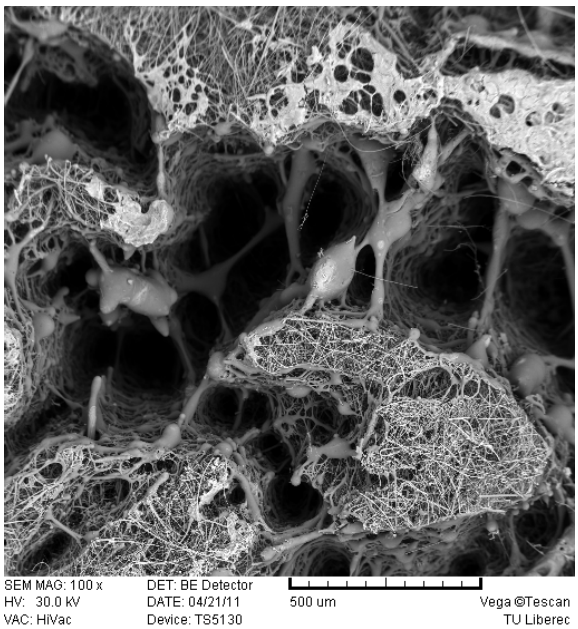

Figure 56 : Zinc particles incorporated into glass fibre mat by laser light treatment.

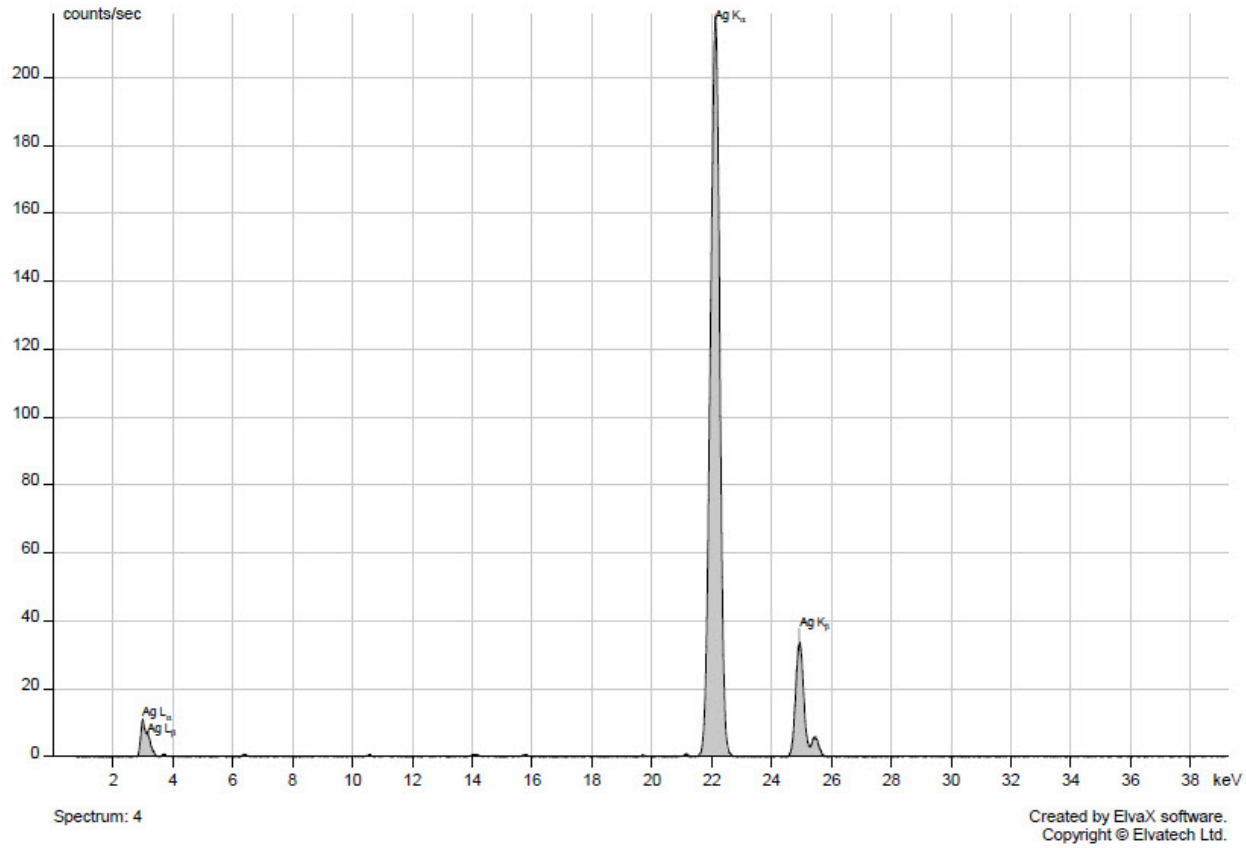

Figure 57 : X-ray fluorescence spectrum view of Silver metal incorporated into the glass fibre by laser light treatment

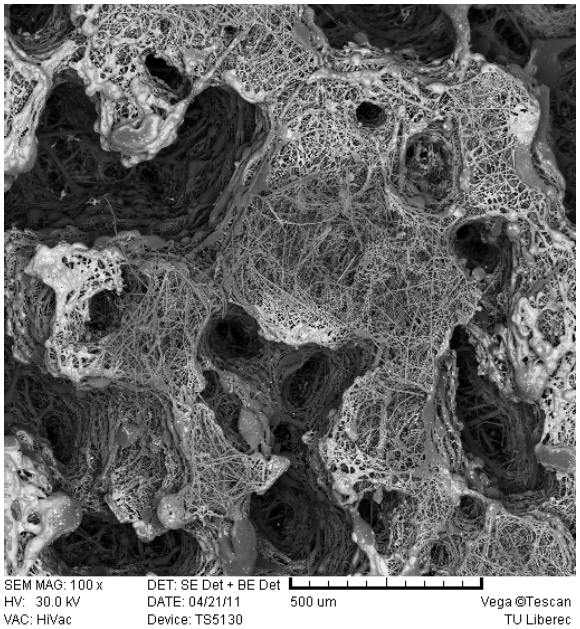

Figure 58 : Silver particles incorporated into glass fibre mat by laser light treatment.

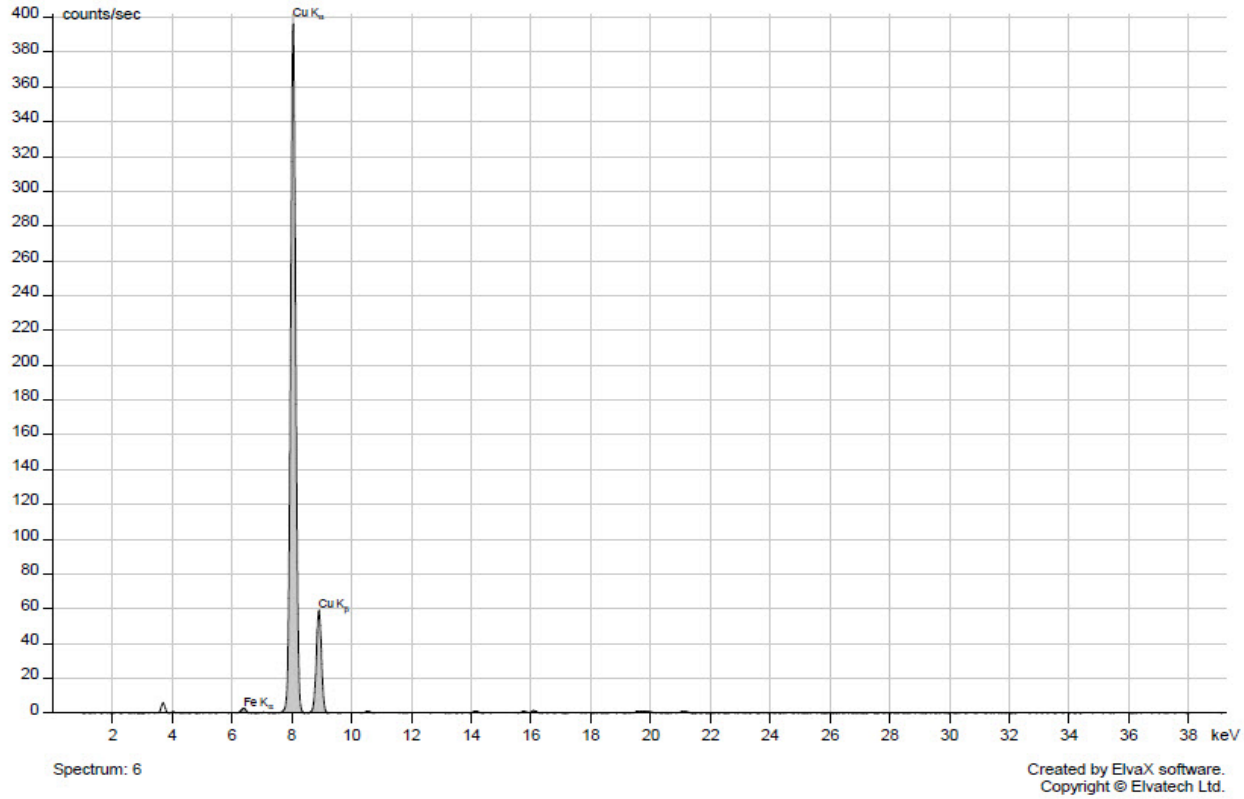

Figure 59 : X-ray fluorescence spectrum view of Copper metal incorporated into the glass fibre by laser light treatment

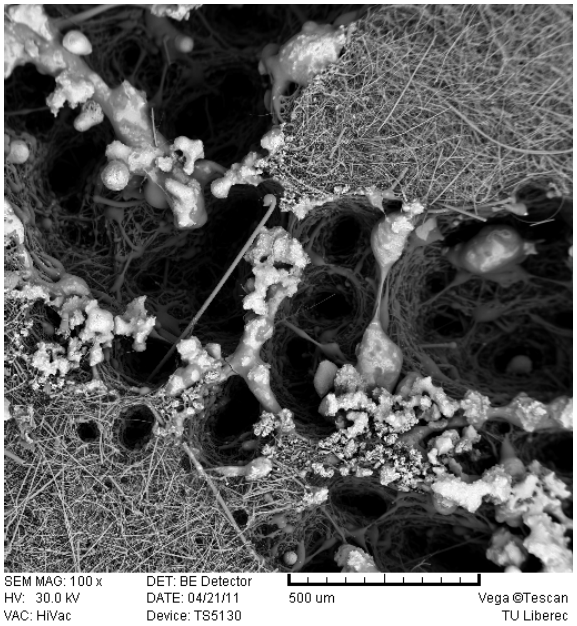

Figure 60 : Copper particles incorporated into glass fibre mat by laser light treatment.

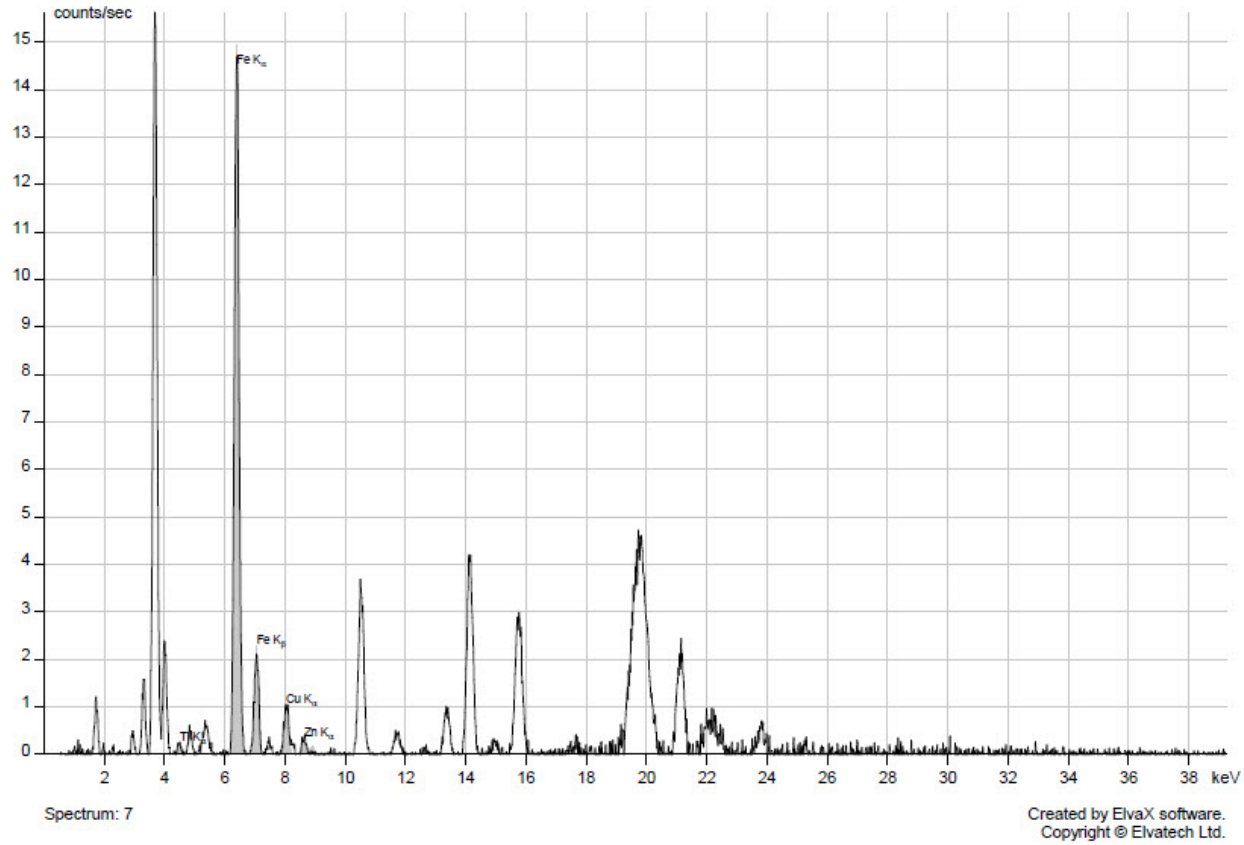

Figure 61 : X-ray fluorescence spectrum view of Iron metal incorporated into the glass fibre by laser light treatment

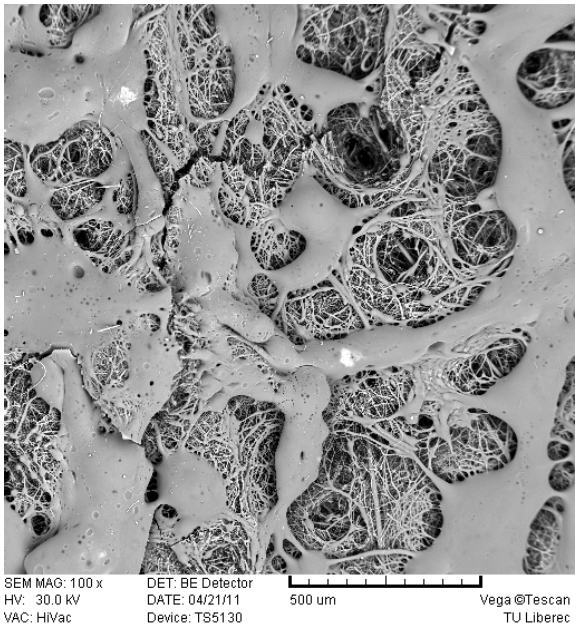

Figure 62: Iron particles incorporated into glass fibre mat by laser light treatment.

As seen in the SEM images and the X-ray fluorescence spectra the metals were incorporated within the glass fibre, the melting and cooling of the glass fibre formed stable bonds around the metal after laser light treatment.

Too high energy used for treatment lead to the formation of melts that solidify to form greater sized, more rigid glass bond spots. These big solid structures affected the mechanical properties of the glass fibre mat negatively because the fibres within the bond spot lost their orientation and strength. The glass fibres that were over bonded lost some of their molecular orientation and strength at the fibre bond interface. The bonding site edge became the stress concentration point where now weaker fibres entered. When the glass fibre was loaded, mechanical mismatch occurred and it resulted in premature failure of fibres at the bond periphery. The glass fibre mat did not lose its mechanical parameters when treated at low energies, 100μs pixel time for the 1.6mm thick glass fibre and 40μs pixel time for the 0.3mm thick glass fibre. It remained quite stable and may be modified in terms of thickness, air permeability and metal ion incorporation.

4. CONCLUSION

Laser light treatment of glass fibre resulted in interesting properties based on the mechanical properties, such as strength, modulus and elongation of the glass fibre mat, the permeability and the thickness of the glass fibre mat. The glass fibre mats were treated with a laser light beam at varying energy intensities and also treated at single laser beam energy intensity while only varying the number of cycles of the used laser light beam intensity.

The glass fibre mats used and analysed were nonwoven structures which were 1.6mm thick and 0.3mm thick samples. The thickness of the glass fibre was determined at a pressure of 50kPa before any treatment was done on the glass fibre mat samples, this pressure determined thickness was given information that came with the untreated glass fibre mat samples.

The 1.6mm thick glass fibre mat was treated with greater (up to 800μs pixel time) laser beam intensities because it had a thicker structure compared to the 0.3mm thick glass fibre mat, but using high laser light beam energies produced negative results because the glass fibre lost its mechanical properties. To high energies up to 800μs pixel time for the 1.6mm thick glass fibre mat and up to 240μs pixel time for the 0.3mm thick glass fibre mat damages the glass fibre mats. The amount of energy needed to cause a noticeable effect is based on the glass fibre mat thickness. At 240μs pixel time the 0.3mm glass fibre mat was completely destroyed while the 1.6mm thick glass fibre mat could be irradiated with energies up to 800μs pixel time. Therefore using lower (100μs pixel time for the 1.6mm thick glass fibre mat and 40μs pixel time for the 0.3mm thick glass fibre mat) laser light energies and laser light treatment cycles for both the 1.6mm thick and 0.3mm thick glass fibre produces positive results since there is no loss in mechanical properties. The glass fibre mat thickness may be reduced using the laser light beam. Laser light beam treatment also allowed for the incorporation of metals in the glass fibre structure. This treatment of glass fibre mat at lower energies also allows the glass fibre to be modified for applications that require heat resistance, chemically resistance, low pressure drop and mechanically stable material properties.

5. REFERENCES

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6. APPENDIX

The figures below show the temperature on the fibre glass surface as it was irradiated with a carbon dioxide laser beam. The glass fibre was irradiated with an intensity of 40μs (pixel time) and at repeated number of cycles.

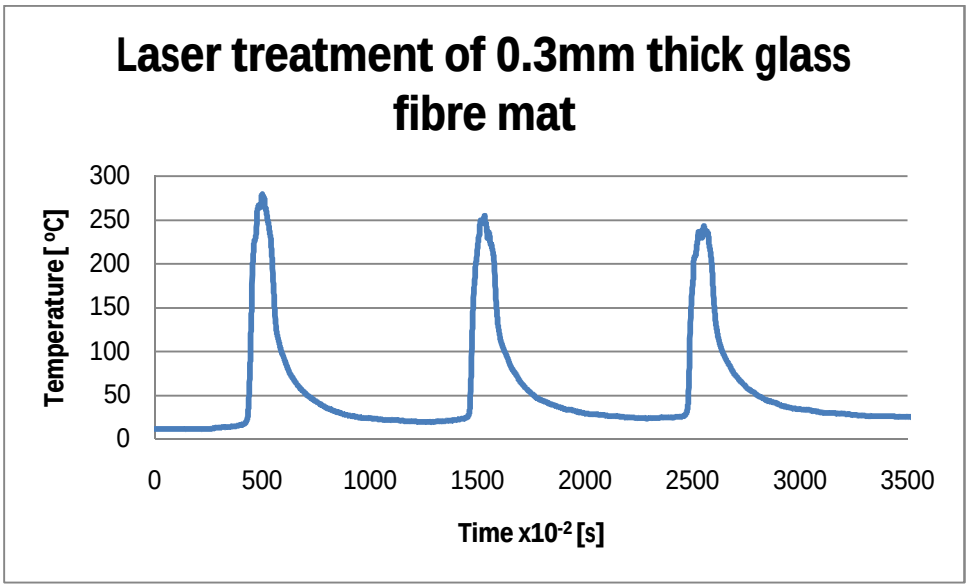

Figure 63 : irradiation of glass fibre mat, 3 cycles at 40μs

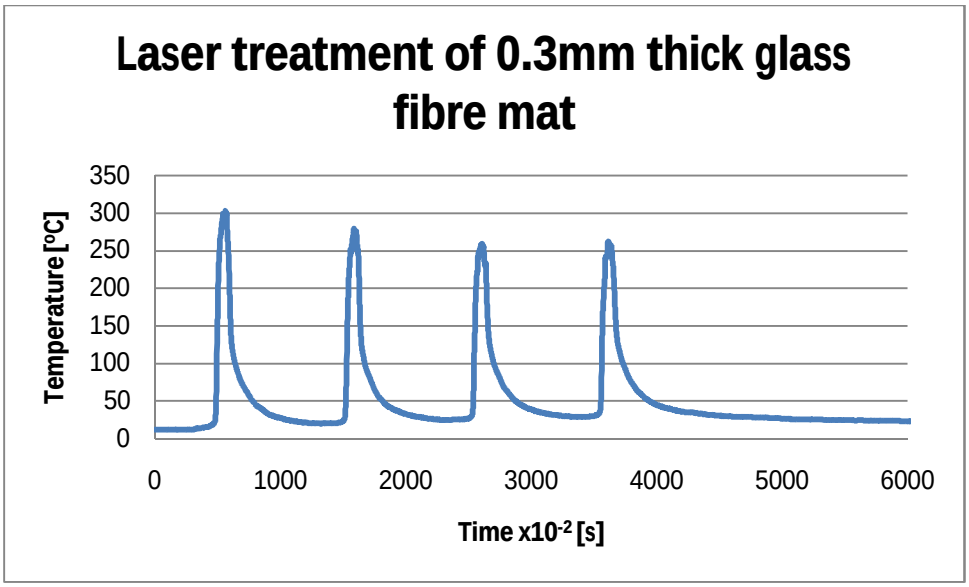

Figure 64 : irradiation of glass fibre mat, 4 cycles at 40µs

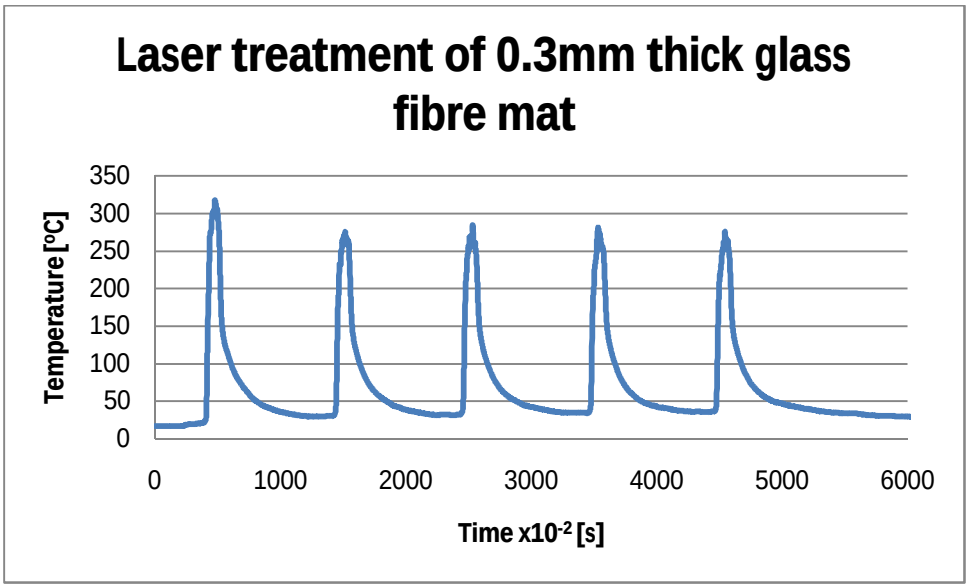

Figure 65 : irradiation of glass fibre mat, 5 cycles at 40µs

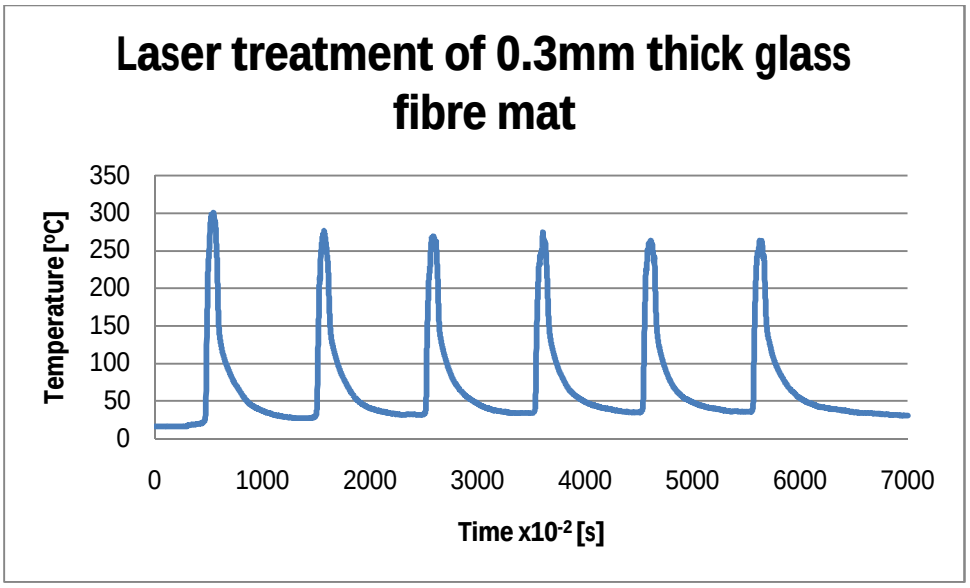

Figure 66 : irradiation of glass fibre mat, 6 cycles at 40µs

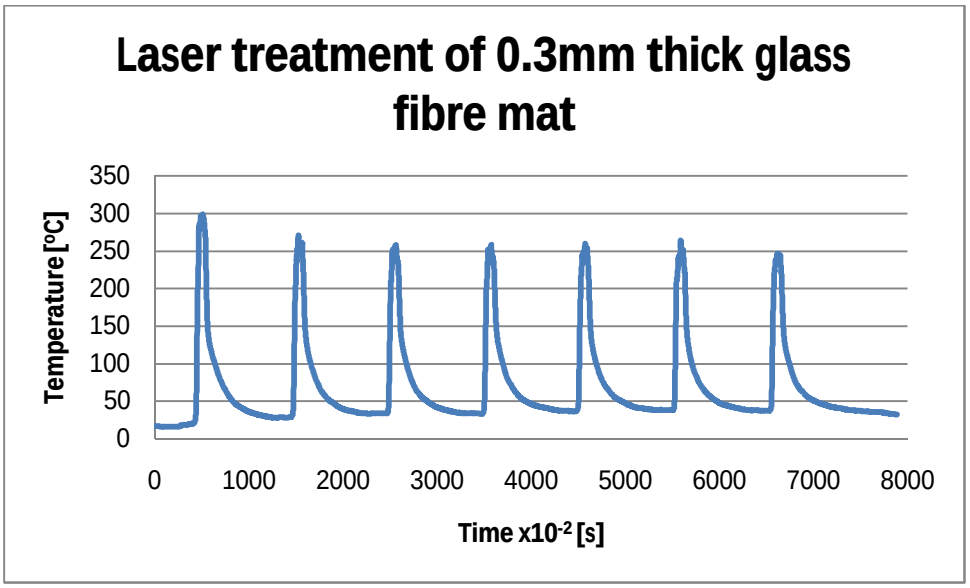

Figure 67 : irradiation of glass fibre mat, 7 cycles at 40µs

The figures below show the temperature on the fibre glass surface as it was irradiated with a carbon dioxide laser beam. The glass fibre was irradiated with an intensity of 100µs (pixel time) and at repeated cycles

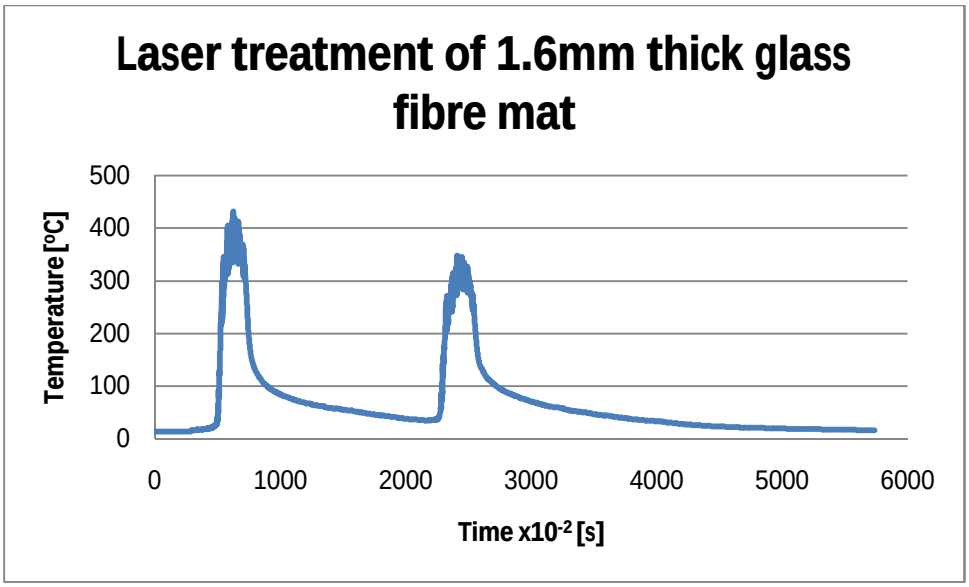

Figure 68 : irradiation of glass fibre mat, 2 cycles at 100µs

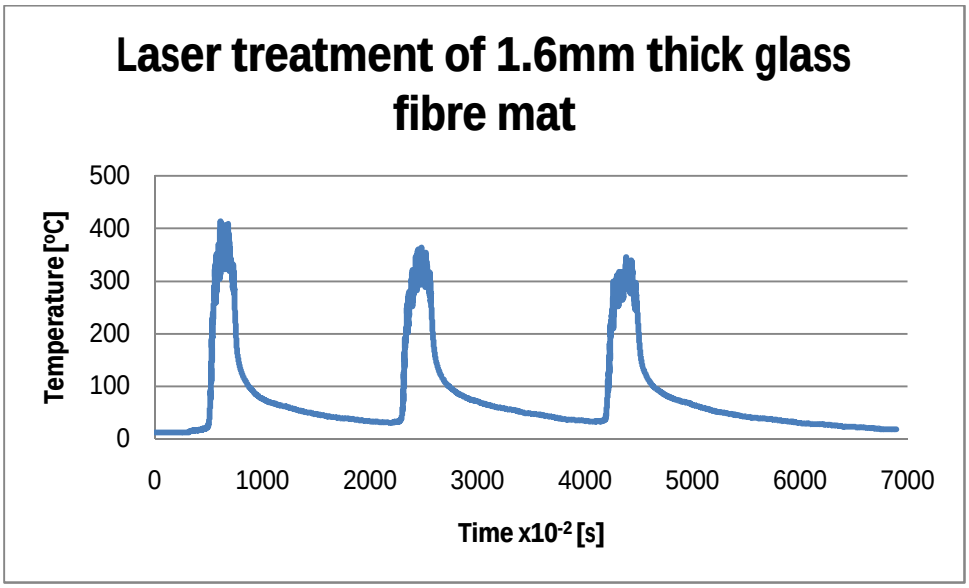

Figure 69 : irradiation of glass fibre mat, 3 cycles at 100µs.

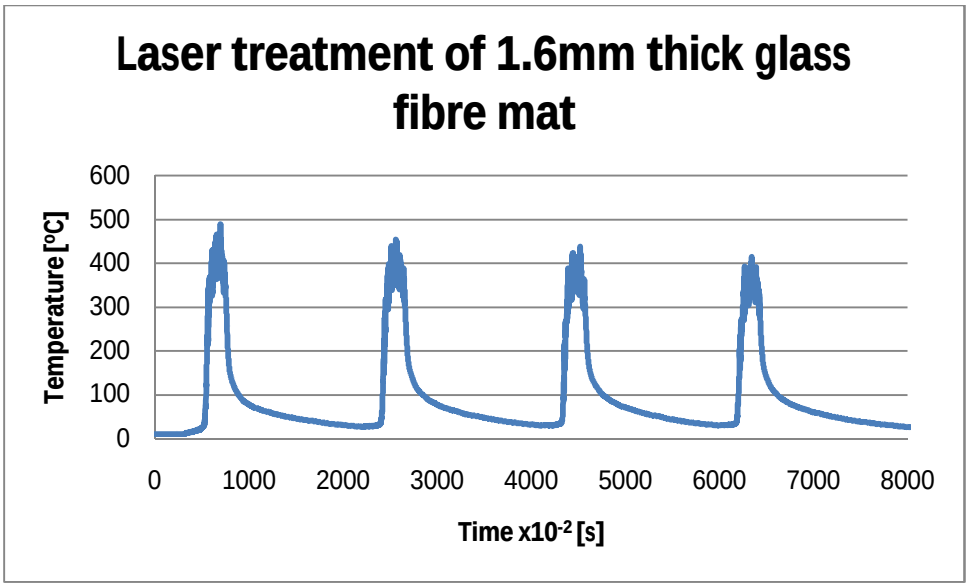

Figure 70 : irradiation of glass fibre mat, 4 cycles at 100µs

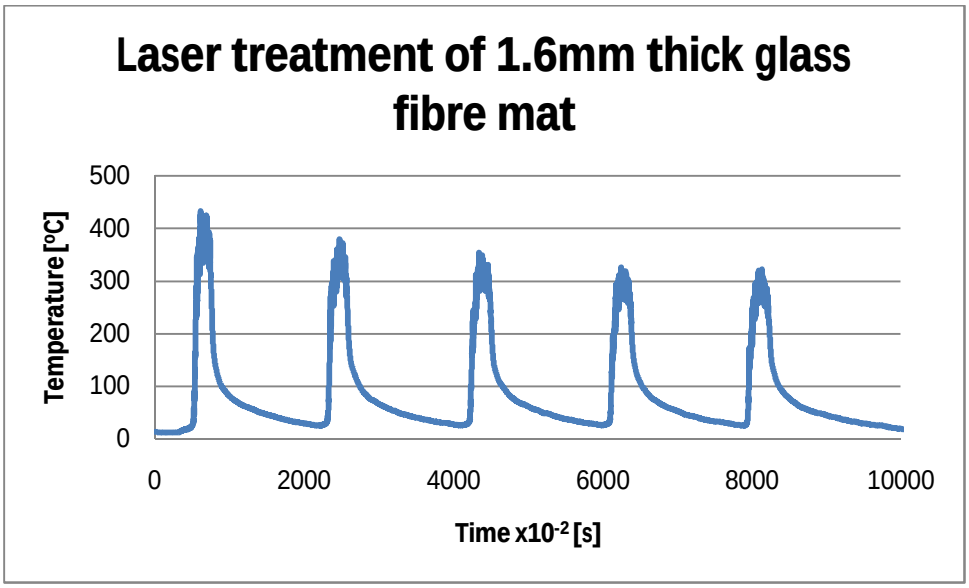

Figure 71 : irradiation of glass fibre mat, 5 cycles at 100µs

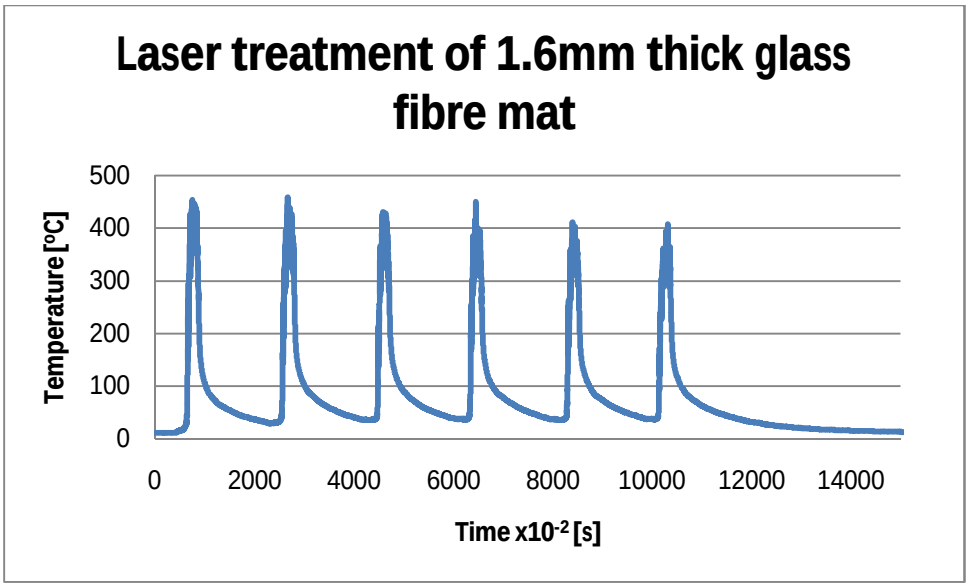

Figure 72 : irradiation of glass fibre mat, 6 cycles at 100µs

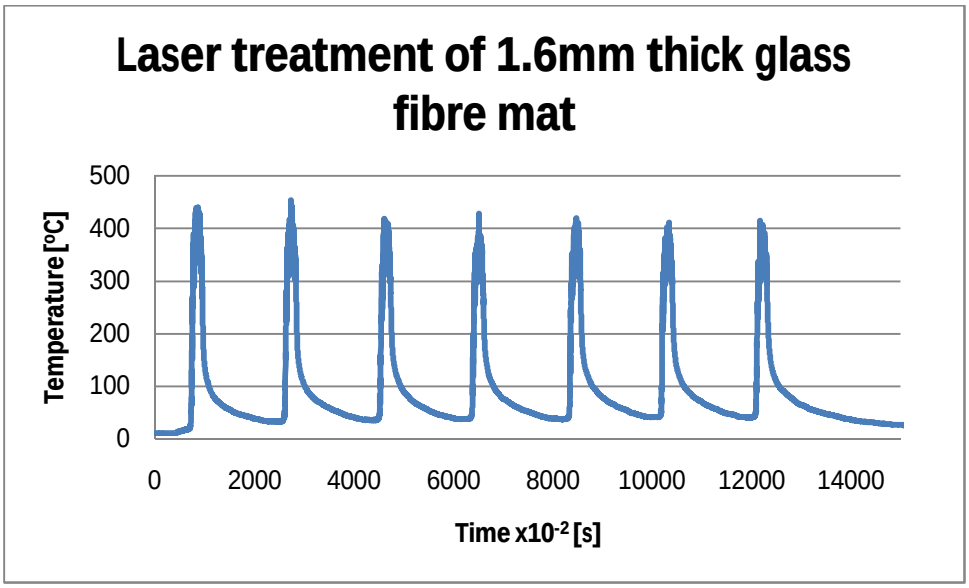

Figure 73 : irradiation of glass fibre mat, 7 cycles at 100µs